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POLLUTION REDUCTION TECHNOLOGY PROGRAM
SMALL JET AIRCRAFT ENGINES
PHASE III – FINAL REPORT

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16. Abstract

A series of Model TFE731-2 engine tests were conducted with the Concept 2 variable-geometry airblast fuel-injector combustion system installed. The Concept 2 system was developed through extensive rig testing conducted in Phases I and II and early in Phase III. The purpose of the engine tests was to establish the emission levels over the selected points which comprise the Environmental Protection Agency (EPA) Landing-Takeoff (LTO) Cycle, determine engine performance with the combustion system, and evaluate the engine acceleration/deceleration characteristics. The hydrocarbon (HC), carbon monoxide (CO), and smoke goals were met. Oxides of nitrogen (NO_x) were above the goal (5.1 vs. 3.7 goal LTO index) for the same configuration that met the other pollutant goals. However, considerably lower NO_x levels (3.9 vs. 3.7 goal LTO index) were achieved in earlier configurations in which CO exceeded the goal. It is likely that a more optimum NO_x/CO compromise could be achieved if extensive hardware modifications beyond the scope of this program were made to increase the contrast in low-power and high-power equivalence ratio obtained from the variable geometry. This would include additional complexity to control the airflow through the dilution and possibly cooling holes. The engine and combustor performance, as well as acceleration/deceleration characteristics, were acceptable.

The Concept 3 staged combustor system was refined from earlier phase development and subjected to further rig refinement testing. This concept met all of the emissions goals. It is expected that further pollutant reductions could be achieved through optimization of the combustion staging.

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FOREWORD

This document is the final report for work performed by AiResearch Manufacturing Company of Arizona, a division of The Garrett Corporation, under Contract NAS3-20819. This program, under the joint sponsorship and direction of the National Aeronautics and Space Administration (NASA) Lewis Research Center and the AiResearch Manufacturing Company of Arizona, accomplished Phase III of the Pollution Reduction Technology Program for Small Jet Aircraft Engines (EPA Class T1).

The authors wish to acknowledge the assistance and guidance rendered for this and previous program phases by Mr. James S. Fear of the NASA Lewis Research Center, who was the NASA Project Manager for the program.

NOTE: Effective January 1, 1981 the company name of AiResearch was changed to the Garrett Turbine Engine Company.

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SUMMARY

The objectives of the Pollution Reduction Technology Program for Small Jet Aircraft Engines are to identify technological approaches that will significantly reduce exhaust emissions of current small gas turbine aircraft engines, and to demonstrate this technology through combustor-rig and full-scale engine testing. The emission goals for this program are the 1979 emissions standards specified on July 17, 1973 for Class T1 aircraft propulsion engines (turbojet and turbofan engines of less than 35.6 kN thrust) by the Environmental Protection Agency (Ref. 1). These standards are formulated over an operating cycle that includes taxi-idle, approach, climbout, and takeoff power settings. Unburned hydrocarbons (HC), carbon monoxide (CO), and oxides of nitrogen (NO_x) levels are measured at each of these four settings, and a time-in-mode factor is applied for each power level. These terms are then added together for each pollutant to arrive at a term referred to as the EPA parameter (EPAP). The maximum EPAP's allowable under the 1979 EPA standards, as established on July 17, 1973 for Class T1 engines, are shown below:

Pollutant	EPAP (lb/1000 lb thrust-hr/cycle)
Unburned hydrocarbons	1.6
Carbon monoxide	9.4
Oxides of nitrogen	3.7

The program has been conducted in three phases. Phase I was a 19-month program in which three distinct combustion system concepts, and their subsequent modifications, were tested in a full-annular combustion rig. The designs were applicable to the AiResearch Model TFE731-2 Turbofan Engine, and the rig duplicated the engine aerodynamics except for compressor exit swirl. Six builds of each of the three concepts were evaluated in screening tests to identify those configurations with the greatest potential for reducing carbon monoxide, unburned hydrocarbons, oxides of nitrogen, and smoke to levels that would meet the program goals.

In Phase II, a 24-month program, the two best concepts identified from Phase I underwent continued refinement in the combustion test rig. The purpose of this testing was to ensure attainment of combustion system performance consistent with overall program goals and engine mechanical and functional compatibility. In addition to the rig testing, two brief engine tests were conducted to correlate engine and rig emission results.

Phase III was a 29-month effort in which the variable-geometry (Concept 2) combustion system underwent full-scale engine tests. These tests were quite extensive and involved emission sampling and performance measurements at power settings from sub-taxi-idle to takeoff. In addition to this steady-state testing, acceleration and deceleration tests were performed to determine engine transient characteristics with the new combustion system. These tests were also duplicated using an Experimental Referee Broad Specification (ERBS) fuel as an addendum to the original program. Prior to the engine test, the Concept 2 engine hardware underwent a limited amount of rig testing to ensure engine compatibility. Rig tests were also performed on the staged injection (Concept 3) configuration to further develop this approach for emissions reduction. This report covers the results of this Phase III testing.

Significant emissons reductions were achieved with the Concept 2 variable geometry system in the TFE731-2 engine as shown in Table I. However, the simultaneous reductions for all pollutants could not be achieved in the same hardware configuration. Primary emphasis was placed upon meeting the HC and CO goals while minimizing NO_x. The table shows the configuration that met the HC and CO goals resulted in NO_x levels considerably above the goal. However, earlier tests had NO_x levels only slightly above the goal, but CO was also above the goal, while HC was below the goal. It is likely that a more optimum NO_x-CO compromise could be achieved if modifications beyond the scope of the program could be made to control the primary zone cooling and/or dilution airflows by using a more complex variable geometry system.

This additional airflow control would increase the difference between the combustor primary zone equivalence ratios at taxi-idle and takeof power, and reduce quenching of the reaction at taxi-idle due to increases in cooling air flow when the swirler valves are closed.

Concept 2 had acceptable pattern factor levels (<0.20), met the Federal Aviation Regulation (FAR) acceleration/deceleration requirement, met the smoke goal, and operated satisfactorily in the engine.

The Concept 3 staged combustion system rig testing results met all the program emission goals, as shown below. It is expected that further reductions could be achieved through additional optimization of the combustion staging.

TABLE I. COMBUSTOR CONCEPT AND POLLUTANT LEVELS.

Configuration	EPAP Lb/1000 Lb Thrust Hrs/Cycle			SAE Smoke No.
	HC	CO	NO_x	
Concept 2 Engine Test (Best CO)	0.20	9.20	5.06	22.5
Concept 2 Engine Test (Best NO_x)	0.50	11.30	3.90	30.0
Concept 3 Rig Test*	0.50	8.40	3.50	9.5
Program Goals	1.60	9.40	3.70	40.0

*Reduced pressure at takeoff condition. Pressure, temperature, and humidity corrections applied (as applicable) to HC, CO, and NO_x . No corrections applied to smoke number.

INTRODUCTION

The Pollution Reduction Technology Program for Small Jet Aircraft Engines was initiated by NASA in December 1974. The overall program objective was to evolve and demonstrate the advanced combustor technology required for the development of EPA Class T1 engines (less than 35.6 kN thrust) to meet aircraft emissions standards. Accordingly, the primary goals of the program involve significant reductions in emissions of carbon monoxide, total unburned hydrocarbons, and total oxides of nitrogen. Reductions in exhaust smoke were also sought; while other combustion performance parameters such as pressure loss, exit temperature, pattern factor, and ignition and relight capability were to be maintained at acceptable levels.

The underlying motivation for this program emanated from public concern for the mounting dangers of air pollution as expressed by Congress in the Clean Air Act Amendments of 1970. In compliance with this legislation, the EPA published standards for control of air pollution from aircraft engines on July 17, 1973 (Ref. 1) that would have required significant reductions in exhaust emissions from Class T1 engines by January 1, 1979. Concerted efforts on the part of the general aviation industry and various government agencies showed the standards to be unachievable by means of design modifications to existing engine components (Ref. 2). Instead, the attainment of emission levels as required by the EPA Standards were considered to depend on the successful development of advanced combustor design concepts, such as those resulting from the NASA Pollution Reduction Technology Program and the Experimental Clean Combustor Program.

In March of 1978, the EPA proposed revisions to its emissions standards that would remove emissions regulations for turbojet and turbofan engines of less than 27.0 kN thrust. While the AiResearch Model TFE731-2 engine falls within this exempt category, the need for technology gained from this Pollution Reduction Technology Program using the Model TFE731-2 engine as a test vehicle will be applicable and valuable to larger engines that are still regulated. This technology will particularly address the needs of engines in the 27.0 to 35.6 kN thrust class, which are within the T1 engine classification and still subject to emissions regulations.

The Pollution Reduction Technology Program for Small Jet Aircraft Engines has been conducted in three phases: Phase I - Combustor Concept Screening, Phase II - Combustor Compatibility Testing, and Phase III - Combustor Engine Testing. The program is based on the use of the Model TFE731-2 combustion system, which is an annular reverse-flow type common to several current production engines in the T1 category.

The results of Phase III combustor engine testing are described in this report. In this phase, the Concept 2 variable-geometry airblast fuel injection concept, which was selected from testing in previous phases, was installed in the Model TFE731-2 demonstrator engine and subjected to a series of tests. These tests established the steady-state performance and emissions characteristics of the engine with the selected combustion concept at the landing-takeoff cycle points and transient engine operation. In addition, the secondary selected combustion concept from previous phases (the Concept 3 staged configuration) was subjected to further rig-test evaluation in Phase III. This concept, which will require extensive rig development before being ready for engine testing, was continued into Phase III because of its demonstrated potential in obtaining dramatic reductions in all pollutants.

The total Class T1 Pollution Reduction Technology Program is described in Chapter I. The equipment and procedures used in the Phase III program are described in Chapter II. Combustor test results and pertinent discussion are presented in Chapter III. Appendixes to the report list combustor hole patterns and experimental test results.

CHAPTER I

POLLUTION REDUCTION TECHNOLOGY PROGRAM FOR SMALL JET AIRCRAFT ENGINES - PROGRAM DESCRIPTION

A. - GENERAL DESCRIPTION

The Pollution Reduction Technology Program for Small Jet Aircraft Engines (EPA Class T1 turbojet and turbofan engines of less than 35.6 kN thrust) is a multiyear effort initiated by the NASA-Lewis Research Center in 1974, and completed in 1980. The overall program objectives were to:

- Identify technology capable of attaining the program emissions-reduction goals consistent with performance constraints.

- Screen and develop configurations employing the technological advancements through full-scale rig testing.

- Demonstrate the most promising approaches in full-scale engine testing.

The AiResearch Model TFE731-2 Turbofan Engine combustion system was selected for the development effort. It is expected that the emissions-control technology derived from this program will be applicable to other engines within the T1 Class, and possibly to other classes as well. It is also anticipated that the results of this program may suggest additional designs or techniques that will merit further evaluation for other specific engine applications or research programs.

B. - PROGRAM GOALS

The program goals for emissions levels were the Environmental Protection Agency 1979 standards for T1 Class engines. The required reductions of unburned hydrocarbons (HC), carbon monoxide (CO), and the oxides of nitrogen (NO_x), were of sufficient magnitude to necessitate advancements in the state-of-the-art. The smoke and performance goals for the program were approximately the same levels as those attained on current Model TFE731-2 engines. The emissions goals were to be achieved without compromise to combustor performance parameters, durability, or existing envelope constraints.

1. Emissions Goals. - The emissions goals for this program were the EPA Class T1 requirements specified on July 17, 1973 for new aircraft gas turbine engines manufactured after January 1, 1979 (Ref. 1). The goals for the individual emissions constituents

and average levels measured on production engines are listed in Table II, and are based on the simulated landing-takeoff (LTO) cycle shown in Table III.

Emissions indexes (EI), expressed as grams of pollutant per kilogram of fuel burned, that approximately correspond to the EPA gaseous emissions standards for Class T1 engines at specific operating conditions are:

Pollutant	Operating Condition	Emissions indexes, g/kg fuel
HC	Taxi-idle	6
CO	Taxi-idle	30
NO_x	Takeoff	10

These EI values are referred to as "goals" throughout the remainder of the report, since meeting these levels would very likely assure that the EPA parameter (EPAP) requirements, which are the actual program goals, would be met.

2. Combustor Performance, Life, and Envelope Goals - The following combustor performance, life, and envelope goals have been established to ensure that the final selected combustion system is compatible with the engine cycle and configuration:

Combustion efficiency:	99 percent at all engine operating conditions
Combustor exit temperature pattern factor[a]:	0.19 at takeoff conditions
Combustor life:	Commensurate with the current Model TFE731-2
Engine relight capability:	Commensurate with the current TFE731-2 relight envelope
Combustor size and shape:	Compatible with Model TFE31-2 installation
Fuel:	ASTM D1655-75 Type Jet A (or equivalent)

---

[a] Pattern factor (PF) =

$$\frac{\text{Max. Combustor Exit Temp.} - \text{Average Combustor Exit Temp.}}{\text{Combustor Temperature Rise}}$$

TABLE II. EMISSIONS COMPARISON - PROGRAM GOALS VS TFE731-2 ENGINE CHARACTERISTICS

Pollutant	Program Goals Gaseous Emissions, lb/1000 lb Thrust-hr/LTO cycle[a]	TFE731-2 Engine Characteristics Gaseous Emissions, lb/1000 lb Thrust-hr/LTO cycle[a,b]	Percent Reduction Needed to Meet Goals
Total unburned hydrocarbons (HC)	1.6	6.6	76
Carbon monoxide (CO)	9.4	17.5	46
Oxides of nitrogen (NO_x)	3.7	5.0	26
Smoke No.	40	36	0

a LTO (landing-takeoff) cycle as defined in Table II.

b Average of six engines measured prior to start of program.

TABLE III. - EPA SPECIFIED LANDING-TAKEOFF CYCLE FOR CLASS T1 ENGINES

Mode	Duration of mode (Minutes)	Engine power setting, (percent of rated power)
Taxi-idle (out)	19.0	5.7[a]
Takeoff	0.5	100
Climbout	2.5	90
Approach	4.5	30
Taxi-idle (in)	7.0	5.7[a]

a Recommended power setting of 0.89 kN thrust for taxi-idle operation of the AiResearch TFE731-2 turbofan in accordance with applicable Federal Aviation Administration Regulations.

C. - PROGRAM PLAN

The Pollution Reduction Technology Program for Small Jet Aircraft Engines was a three-phase effort, with each phase independently funded:

- o Phase I - Combustor screening tests of low-emission concepts
- o Phase II - Combustor refinement and optimization tests
- o Phase III - Engine testing with selected combustor concept(s).

1. Phase I Program. - Phase I involved the design, rig testing, and data analysis of a number of candidate approaches for reducing HC, CO, NO_x, and smoke emissions. The objective of this phase was to identify and develop emission control technology concepts. A detailed description of the Phase I Program and the results are presented in Ref. 3.

2. Phase II Program. - During Phase II, the two most promising combustor configurations identified in Phase I underwent more extensive testing. A component test rig was used to develop systems that optimized emissions reductions consistent with acceptable combustion-system performance required in an engine application. Therefore, Phase II testing entailed development in the areas of off-design-point operation, lean-stability and altitude-relight capability, and exit-temperature profile and pattern factor. In addition to the rig tests, a provision was made in Phase II to conduct limited engine tests using test-rig adaptive hardware, with the intention of obtaining a correlation between the emission levels measured on the engine and rig. These tests were confined to brief correlation checks, and no refinement or development work (scheduled for Phase III) was conducted in Phase II. A description of the Phase II program activity and results are presented in Ref. 4.

3. Phase III Program. - The most promising combustion system, developed and refined through Phases I and II, was assembled on a Model TFE731-2 engine and underwent a series of tests to demonstrate the actual performance and emissions characteristics in an engine environment. An alternate combustion system design was rig tested for further development. A description of the Phase III program activity and results are presented in Chapters II and III of this report.

D. - PROGRAM SCHEDULE

The program schedule is shown in Figure 1. Phase I was a 19-month technical effort. Phase II was completed in 24 months. Phase III was a 29-month effort, and was completed in May 1980.

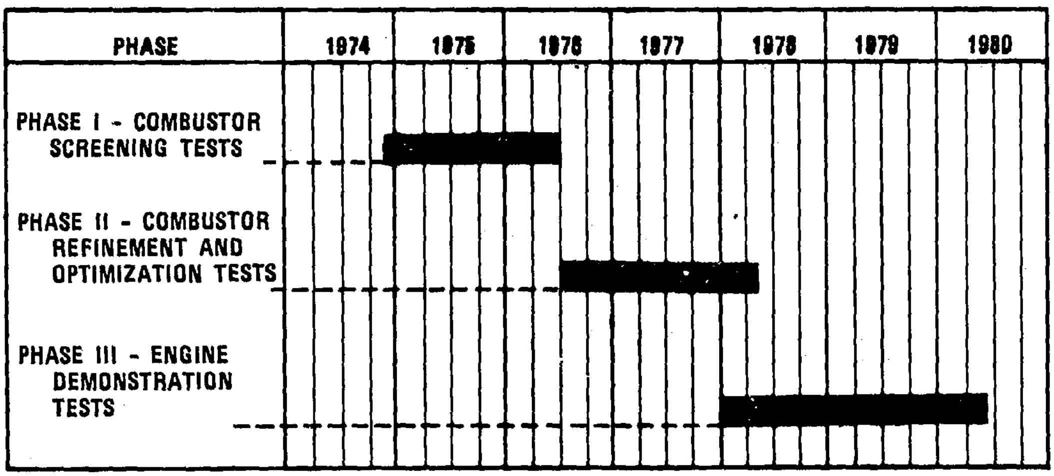

Figure 1. Program Schedule.

CHAPTER II

PHASE III PROGRAM - EQUIPMENT AND PROCEDURES

A. - INTRODUCTION

This chapter contains a description of the AiResearch Model TFE731-2 engine and its combustion system. The Model TFE731-2 was selected as being representative of current-technology turbofan engines of EPA Class T1, and to serve as the baseline for comparison for the program results. In addition, the test facilities and equipment, emissions sampling and analysis instrumentation, test procedures, and data-analysis procedures and methods are described.

B. - BASELINE TEST ITEMS DESCRIPTION AND PERFORMANCE

1. Model TFE731 Turbofan Engine - General Description. - The Model TFE731-2 engine is a 15.6 kN thrust engine, which is the lower-power version of the two Model TFE731 engine models currently in production (the other version, designated Model TFE731-3, is rated at 16.5 kN thrust). Both engines are of a two-spool, geared-front-fan design, with a bypass ratio of 2.67. The fan is coupled through a planetary gearbox to the low-pressure (LP) spool, which consists of a four-stage axial compressor and a three-stage axial turbine. The high-pressure (HP) spool consists of a single-stage centrifugal compressor and a single-stage axial turbine. A photograph of the engine is shown in Figure 2. Overall engine dimensions and weight are included in Figure 3, and details regarding combustor design are shown in Figure 4.

Performance characteristics for the Model TFE731-2 engine are listed in Table IV. A plot of the Model TFE731-2 operating and starting envelope is presented in Figure 5.

TABLE IV. KEY ENGINE PERFORMANCE PARAMETERS.

Thrust, kN:	
Sea-level takeoff (maximum thrust)	15.6
Maximum cruise (12,192 m, M=0.8)	3.36
Thrust specific fuel consumption, kg/N-hr:	
Sea-level takeoff (maximum thrust)	0.048
Maximum cruise (12,192 m, M=0.8)	0.082
Noise level, EPNdb:	
Sea-level takeoff	82.6

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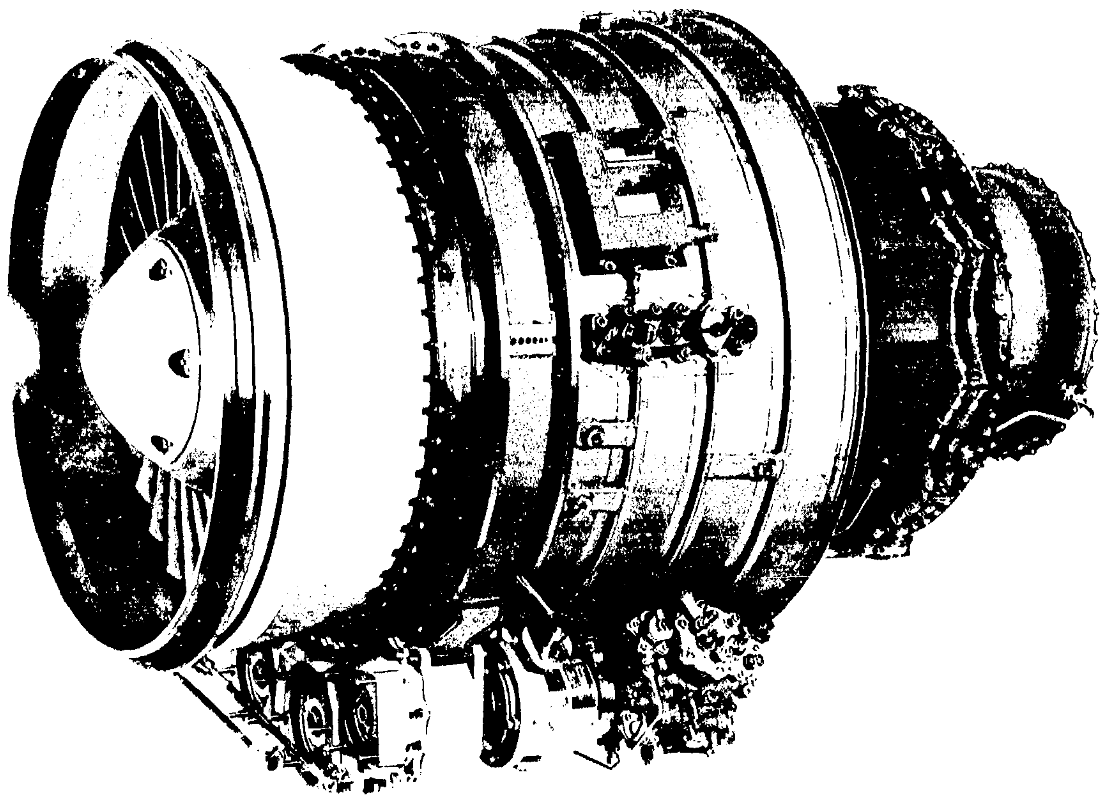


Figure 2. Left-Front View of AiResearch Model TFE731 Turbofan Engine.

ENGINE WEIGHT: 329 kg

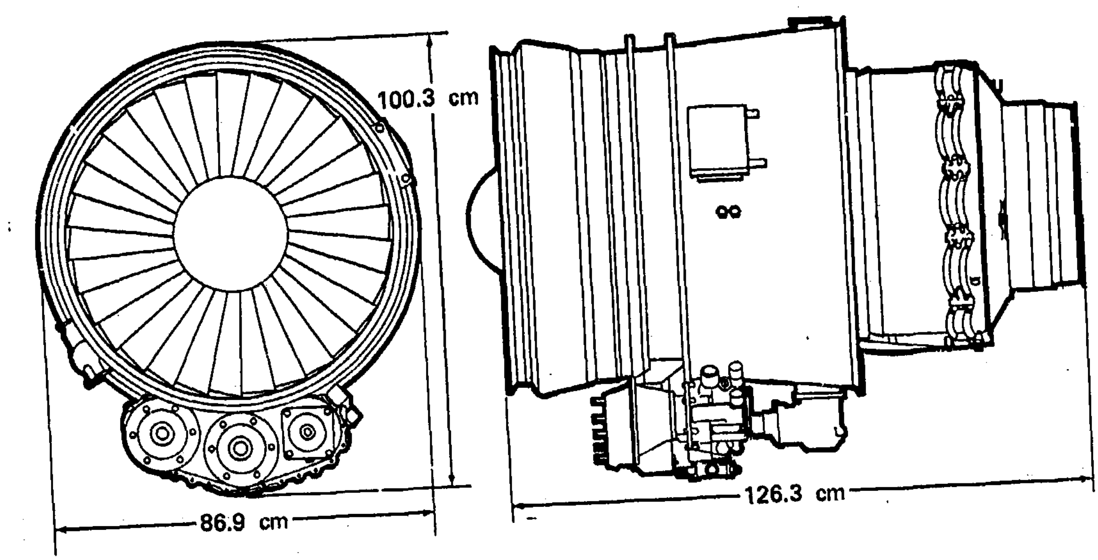


Figure 3. Engine Envelope Dimensions.

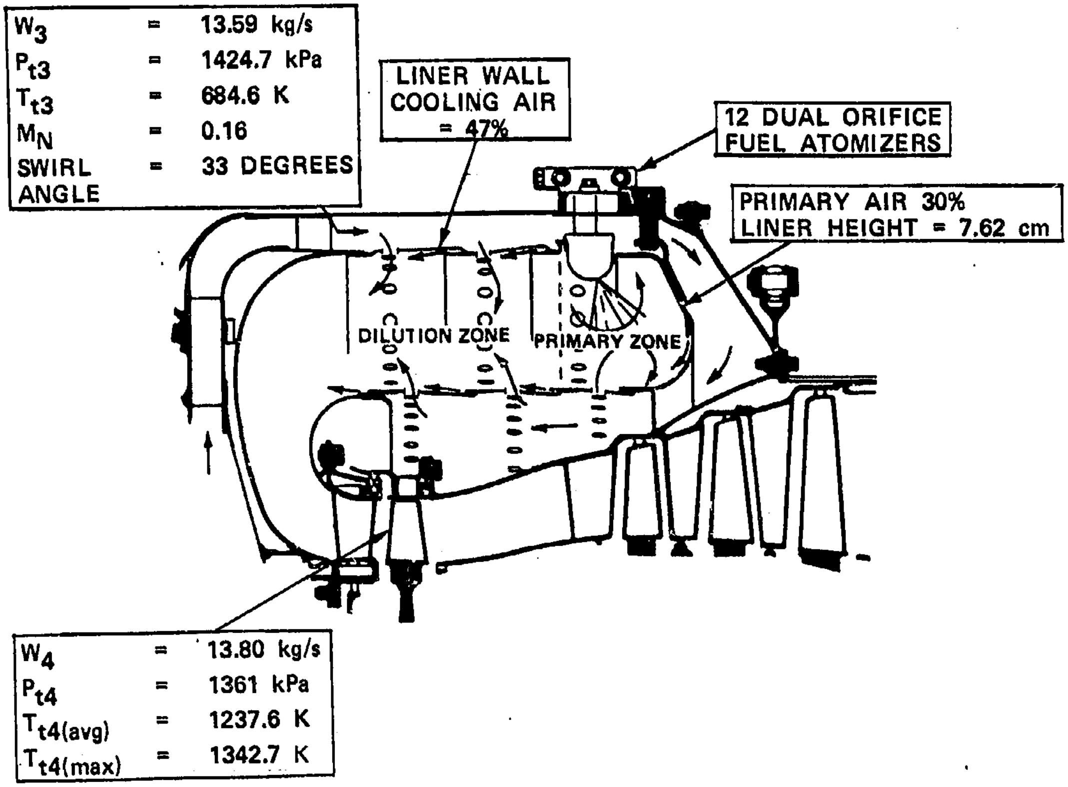


Figure 4. Reverse-Flow Annular Combustor System, Sea-Level, Standard-Day, Static Conditions.

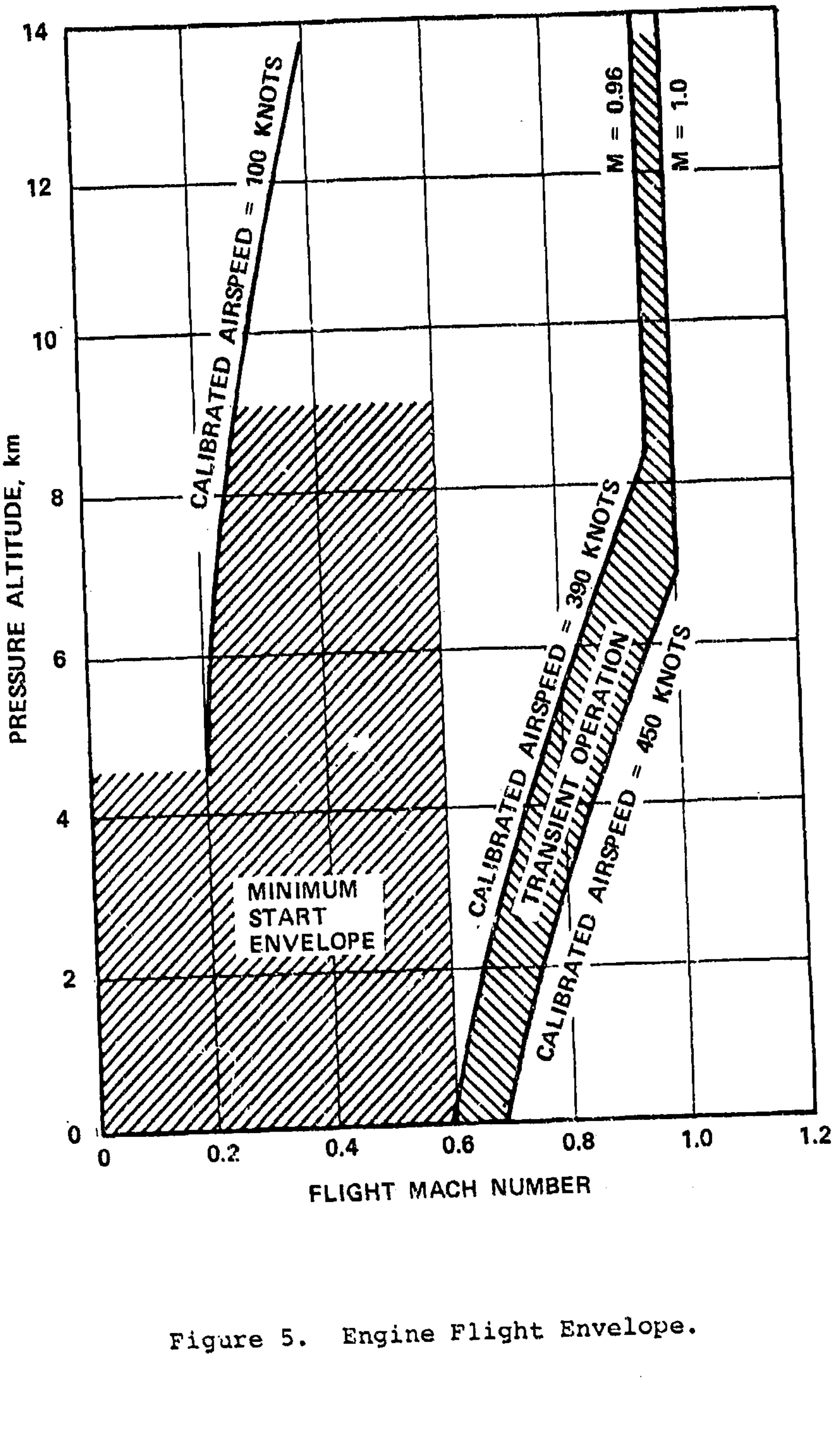


Figure 5. Engine Flight Envelope.

2. Model TFE731-2 Combustion System Description. - The Model TFE731-2 combustor is of a reverse-flow annular design. The combustor liner consists of an inner and an outer panel connected by a dome. Cooling bands (two on the outer and three on the inner) are brazed to these panels. Fuel is injected into the combustor through 12 dual-orifice fuel nozzles inserted radially through the liner outer panel near the dome. The fuel spray cone is angled 35 degrees toward the dome, and injects nearly tangentially around the combustor annulus in the direction of the inlet air swirl. A single fuel-flow-divider valve is used to regulate fuel flow between the primary and secondary flow circuits. Ignition and initial engine acceleration are performed on primary fuel only; the secondary fuel flow starts slightly before the taxi-idle power setting is reached. The ignition system consists of two air-gap igniters connected to a capacitance-discharge ignition unit. The igniters are located in the bottom quadrant of the combustor, and align axially with the fuel nozzles. The key combustor-operating parameters at the taxi-idle and takeoff power settings are listed in Table V.

3. Baseline Pollution Levels. - At the onset of Phase I of the program, rig testing was performed on current production combustion system hardware to establish baseline emissions values. These data, together with the program goals, are shown in Table VI for the taxi-idle and simulated takeoff points. The takeoff goals were calculated from Phase II rig-to-engine correlations (and compensated for the differences in rig and engine combustor pressure).

C. - TEST RIG AND FACILITIES

1. Pressure Rig and Instrumentation. - The pressure rig was originally designed for use in the development of the combustion system for the production Model TFE731 engine. Only minor modifications and the refurbishment of hot-end components were required for use during this program. A cross-section layout of the rig is shown in Figure 6. The compressor diffuser, deswirl vanes, and inner and outer transition liners were all reworked engine components, and ensured that the combustion system aerodynamics simulated engine conditions as nearly as possible. A traversing instrumentation drum was located at the axial plane of the turbine stator inlet, and contained the combustor-exit instrumentation. The inlet instrumentation was mounted on the combustor plenum in the vicinity of the compressor deswirl vanes. A listing of the instrumentation is given in Tables VII and VIII for each of the combustor concepts tested in Phase III.

2. Combustor Inlet Instrumentation. - Figure 7 shows the circumferential location of the combustor inlet instrumentation for Concept 2. There were four total-pressure rakes located at 90-degree intervals around the plenum. Probe angles were adjustable with respect to the axial position, and the probes were set

TABLE V. KEY OPERATING PARAMETERS OF THE TFE731-2 COMBUSTOR

Parameter	Taxi-Idle	Takeoff
Combustor airflow, kg/s	2.31	13.59
Compressor discharge total pressure, kPa	202.1	1425.0
Combustor pressure loss, percent	3.0	4.5
Compressor discharge temperature, K	369.9	684.6
Combustor discharge temperature, K	754.4	1257.6
Combustor discharge pattern factor	0.35	0.19
Combustor fuel flow, kg/hr	87.3	754.3

TABLE VI. TEST RIG BASELINE EMISSION VALUES

	Taxi-idle emissions		Takeoff emissions	
	HC, g/kg fuel	CO, g/kg fuel	NO_x, g/kg fuel	Smoke
1979 production*	20.6	58.8	11.5	16
Goals (compensated for rig conditions)	6.0	30.0	7.0	12
Required reduction, percent	70.9	49	39.4	25

*As measured at test rig conditions, (414 kPa, maximum, at takeoff, as compared with engine takeoff pressure of 1425 kPa).

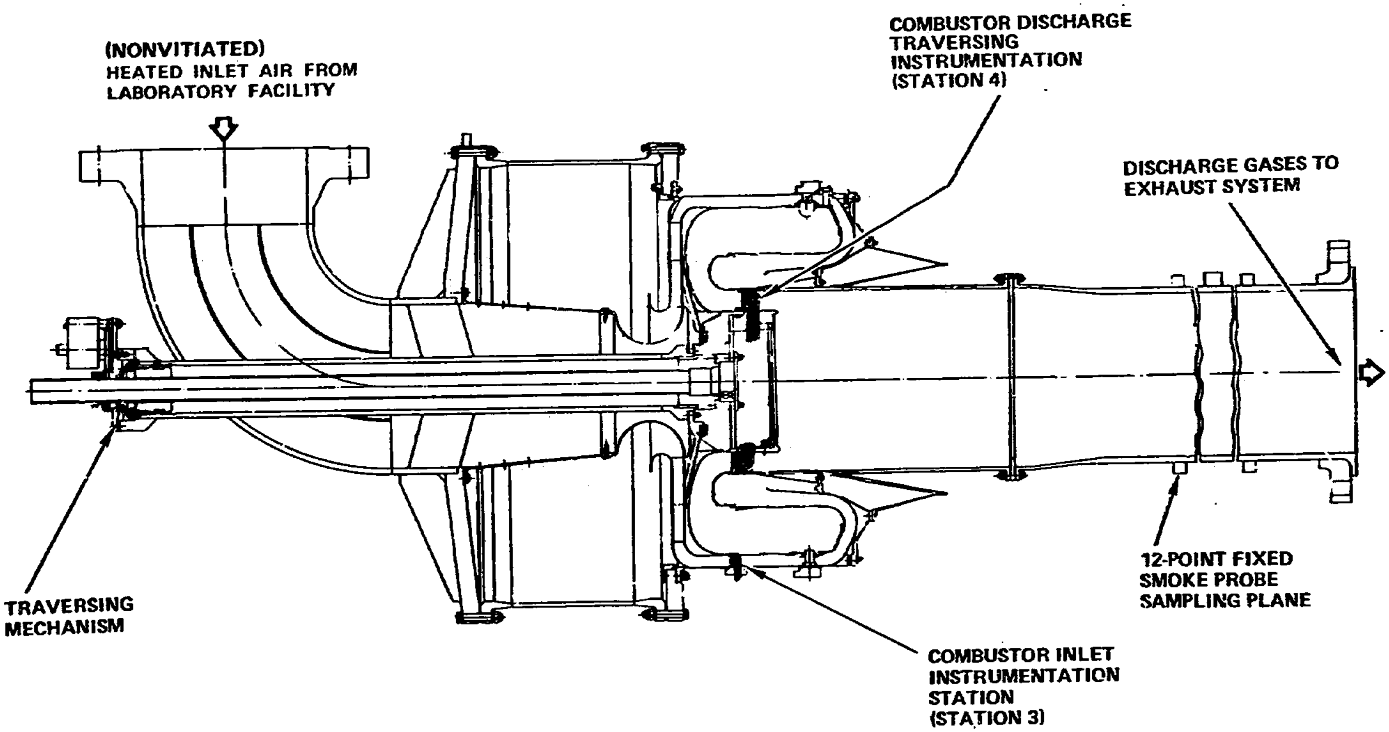


Figure 6. Full-Scale Reverse-Flow Annular Combustor Test Rig

TABLE VII. - COMBUSTOR PRESSURE RIG INSTRUMENTATION LIST, CONCEPT 2.

Parameter	Symbol	Angular Position, Degrees	Immersion, cm	Sensor Type (Dimensions in cm)
Combustor Inlet Static Pressure	P_{S31}	345	0	0.140 Dia. Tap
Combustor Inlet Static Pressure	P_{S32}	75	0	0.140 Dia. Tap
Combustor Inlet Static Pressure	P_{S33}	165	0	0.140 Dia. Tap
Combustor Inlet Static Pressure	P_{S34}	255	0	0.140 Dia. Tap
Combustor Inlet Total Pressure	P_{T311}	345	0.413	0.317 Dia. Pitot Tubes
Combustor Inlet Total Pressure	P_{T312}	345	0.730	0.317 Dia. Pitot Tubes
Combustor Inlet Total Pressure	P_{T313}	345	1.048	0.317 Dia. Pitot Tubes
Combustor Inlet Total Pressure	P_{T314}	345	1.365	0.317 Dia. Pitot Tubes
Combustor Inlet Total Pressure	P_{T321}	75	0.413	0.317 Dia. Pitot Tubes
Combustor Inlet Total Pressure	P_{T322}	75	0.730	0.317 Dia. Pitot Tubes
Combustor Inlet Total Pressure	P_{T323}	75	1.048	0.317 Dia. Pitot Tubes
Combustor Inlet Total Pressure	P_{T324}	75	1.365	0.317 Dia. Pitot Tubes
Combustor Inlet Total Pressure	P_{T331}	165	0.413	0.317 Dia. Pitot Tubes
Combustor Inlet Total Pressure	P_{T332}	165	0.730	0.317 Dia. Pitot Tubes
Combustor Inlet Total Pressure	P_{T333}	165	1.048	0.317 Dia. Pitot Tubes
Combustor Inlet Total Pressure	P_{T334}	165	1.365	0.317 Dia. Pitot Tubes
Combustor Inlet Total Pressure	P_{T341}	255	0.413	0.317 Dia. Pitot Tubes
Combustor Inlet Total Pressure	P_{T342}	255	0.730	0.317 Dia. Pitot Tubes
Combustor Inlet Total Pressure	P_{T343}	255	1.048	0.317 Dia. Pitot Tubes
Combustor Inlet Total Pressure	P_{T344}	255	1.365	0.317 Dia. Pitot Tubes
Combustor Inlet Total Temperature	T_{T31}	30	0.889	CA Thermocouples bead-type half-shielded (all T_{T3} locations)
Combustor Inlet Total Temperature	T_{T32}	120	0.889	
Combustor Inlet Total Temperature	T_{T33}	210	0.889	
Combustor Inlet Total Temperature	T_{T34}	330	0.889	
Combustor Discharge Static Pressure	P_{S41}	Rotating Rake	0	0.175 Dia. Tap
Combustor Discharge Total Pressure	P_{T41}		0.343	0.317 Dia. Pitot Tubes
Combustor Discharge Total Pressure	P_{T42}		0.775	0.317 Dia. Pitot Tubes
Combustor Discharge Total Pressure	P_{T43}		1.283	0.317 Dia. Pitot Tubes
Combustor Discharge Total Pressure	P_{T44}		1.816	0.317 Dia. Pitot Tubes
Combustor Discharge Total Pressure	P_{T45}		2.324	0.317 Dia. Pitot Tubes
Combustor Discharge Total Pressure	P_{T46}		2.857	0.317 Dia. Pitot Tubes
Combustor Discharge Total Temp.	T_{T41}		0.349	Pt/Pt and 10% Rh Thermocouples shielded (all T_{T4} locations)
Combustor Discharge Total Temp.	T_{T42}		0.768	
Combustor Discharge Total Temp.	T_{T43}		1.289	
Combustor Discharge Total Temp.	T_{T44}		1.810	
Combustor Discharge Total Temp.	T_{T45}		2.330	
Combustor Discharge Total Temp.	T_{T46}		2.850	
Sample Gas Temperature	T_{SG1}	-	-	CA Thermocouples shielded
Sample Gas Temperature	T_{SG2}	-	-	CA Thermocouples shielded

TABLE VIII. COMBUSTOR PRESSURE RIG INSTRUMENTATION LIST, CONCEPT 3.

Parameter	Symbol	Angular Position Degrees	Immersion cm	Sensor Type
Combustor Inlet Static Pressure	P_{S31}	60	0	0.140 cm. Dia. Tap
Combustor Inlet Static Pressure	P_{S32}	150	0	0.140 cm. Dia. Tap
Combustor Inlet Static Pressure	P_{S33}	240	0	0.140 cm. Dia. Tap
Combustor Inlet Static Pressure	P_{S34}	330	0	0.140 cm. Dia. Tap
Combustor Inlet Total Pressure	P_{T31}	356	0.89	0.3175 cm. Dia. Pitot Tube
Combustor Inlet Total Pressure	P_{T32}	86	0.89	0.3175 cm. Dia. Pitot Tube
Combustor Inlet Total Pressure	P_{T33}	176	0.89	0.3175 cm. Dia. Pitot Tube
Combustor Inlet Total Pressure	P_{T34}	266	0.89	0.3175 cm. Dia. Pitot Tube
Combustor Inlet Total Temperature	T_{T31}	42	0.89	CA Thermocouples bead-
Combustor Inlet Total Temperature	T_{T32}	132	0.89	type half-shielded
Combustor Inlet Total Temperature	T_{T33}	222	0.89	
Combustor Inlet Total Temperature	T_{T34}	312	0.89	
Combustor Discharge Static Pressure	P_{S41}	Rotating Rake	0	0.175 cm. Dia. Tap
Combustor Discharge Total Pressure	P_{T41}		0.34	0.3175 cm. Dia. Pitot Tube
Combustor Discharge Total Pressure	P_{T42}		0.77	0.3175 cm. Dia. Pitot Tube
Combustor Discharge Total Pressure	P_{T43}		1.28	0.3175 cm. Dia. Pitot Tube
Combustor Discharge Total Pressure	P_{T44}		1.82	0.3175 cm. Dia. Pitot Tube
Combustor Discharge Total Pressure	P_{T45}		2.32	0.3175 cm. Dia. Pitot Tube
Combustor Discharge Total Pressure	P_{T46}		2.86	0.3175 cm. Dia. Pitot Tube
Combustor Discharge Total Temperature	T_{T41}		0.35	Pt/Pt and 10% Rh
Combustor Discharge Total Temperature	T_{T42}		0.77	Thermocouple shielded
Combustor Discharge Total Temperature	T_{T43}		1.28	
Combustor Discharge Total Temperature	T_{T45}		2.33	
Combustor Discharge Total Temperature	T_{T46}		2.85	
Sample Gas Temperature	T_{SG1}	-	-	CA Thermocouples shielded
Sample Gas Temperature	T_{SG2}	-	-	CA Thermocouples shielded

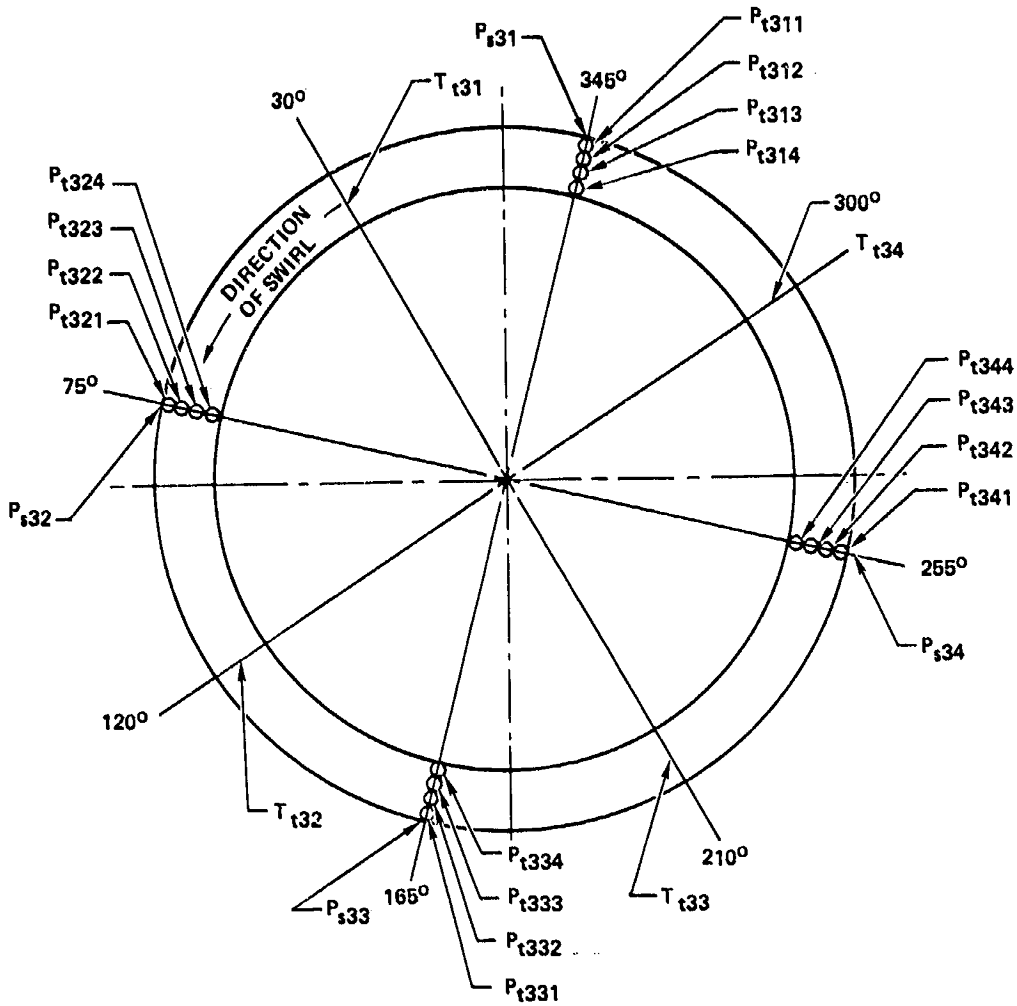


Figure 7. Circumferential Location of Inlet Instrumentation for Concept 2 (View Looking into Combustion Chamber Liner).

to compensate for the airflow swirl angle of approximately 35 degrees to obtain the maximum total-pressure value. These total-pressure rakes consisted of four-element probes identical to the probes used in Phase II. Immediately upstream of each total-pressure rake was a static-pressure wall tap for measurement of combustor inlet static pressure. Four inlet total-temperature thermocouples were located at the same axial plane as the total-pressure rakes, and circumferentially spaced halfway (45 degrees) between the rakes. The thermocouples were Chromel-Alumel with a closed bead. The bead was immersed halfway into the inlet channel.

For Concept 3, single-element total-pressure probes were used because of interference with the main-stage fuel manifolds. The instrumentation stations were spaced circumferentially, at 12 intervals, with four points 90 degrees apart used for the total pressure, static pressure, and inlet temperature (see Figure 8).

3. Combustor-Discharge Instrumentation. - The combustor-discharge instrumentation was located in the plane of the turbine stator inlet. The drum was connected to a stepping motor that indexed the drum in 10-degree increments. The rakes were canted at a 20-degree angle to compensate for combustor exit air swirl. These rakes were:

- A six-element platinum/platinum-10-percent rhodium thermocouple rake
- A six-element total-pressure rake with one static-pressure tap
- A four-point, water-cooled emissions rake.

The lines from these rakes were inserted into the traversing drum where they entered the instrumentation shaft through gas-tight compression fittings. The cooling-water lines for the emission probe also entered the shaft through compression fittings. These rig instrumentation lines were terminated at the end of the shaft and connected to facility lines. The emissions rake consisted of four 3.17-mm diameter stainless-steel probes that were connected to a common 6.35-mm diameter stainless-steel tube. The tips of the four probes were located in the combustor exhaust-gas stream, and the sample gases passed through them and into the common collector. Surrounding the collector was a water jacket that contained inlet and exit ports for cooling water. Water was supplied through a closed-circuit system connected to the facility cooling tower. Thermocouples were located in the emission sample gas stream (one near the probe and the other at the exit of the instrumentation shaft) to monitor the sample temperature. The cooling water flow rate was adjusted to maintain the desired 422 to 881 K sample temperature.

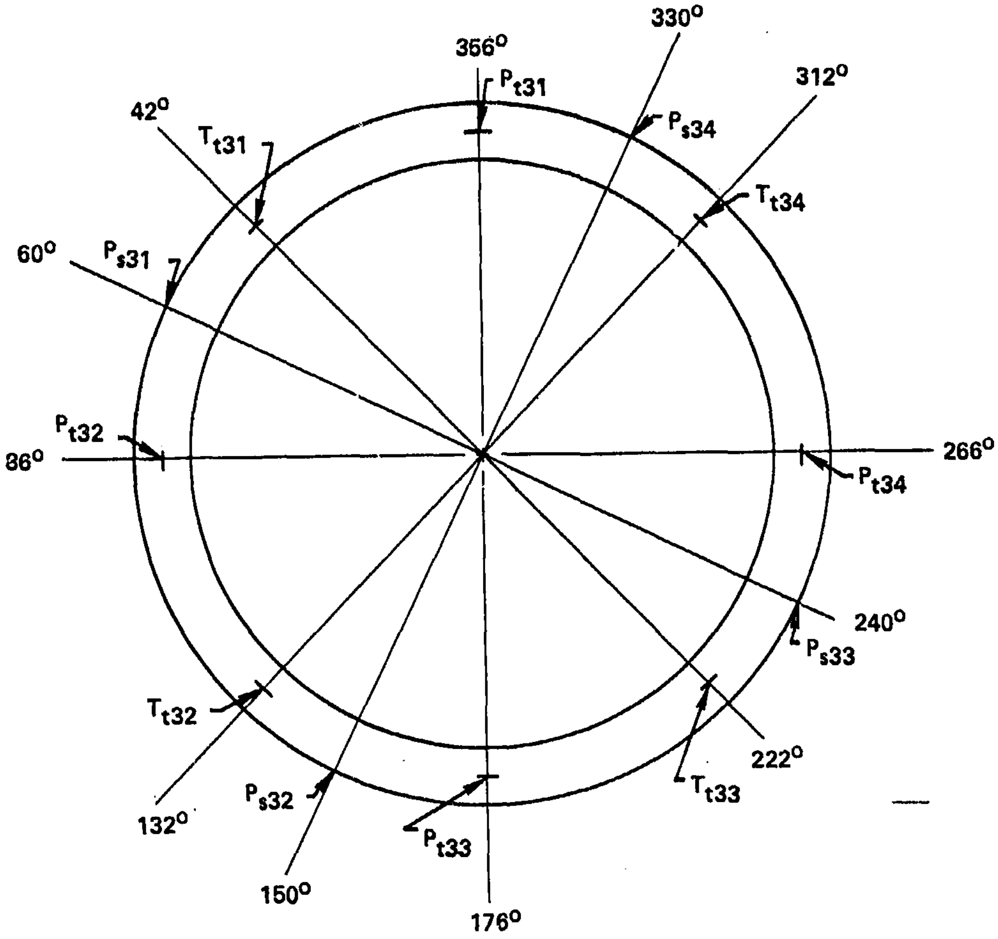


Figure 8. Circumferential Location of Inlet Instrumentation for Concept 3 (View Looking into Combustion Chamber Liner.)

In addition to the emissions probe on the instrumentation drum, a fixed-position smoke-sampling rake was located in the tailpipe downstream of the exhaust-gas mixing basket. This rake consisted of four 6.35-mm stainless-steel probes externally manifolded and inserted through the rig tailpipe. Each tube had three 0.8-mm orifices drilled through the wall and spaced on centers of equal areas for the tailpipe.

4. Combustion Component Test Facility. - The combustion facility has the capability of supplying up to 4.08 kg/s of unvitiated air at a pressure and temperature of 690 kPa and 700 K, respectively. Higher airflow rates are possible with corresponding decreases in pressure. The facility is instrumented to measure pertinent air and fuel flow rates, temperatures, and pressures necessary to determine performance factors such as efficiency, discharge temperature, pattern factor, combustor total pressure drop, ignition, and emissions.

Pressures from 0 to 34.5 MPa can be measured with the use of pressure transducers. These transducers were used to measure those parameters necessary for the determination of airflow rate. Rig pressures were measured with a Scanivalve transducer.

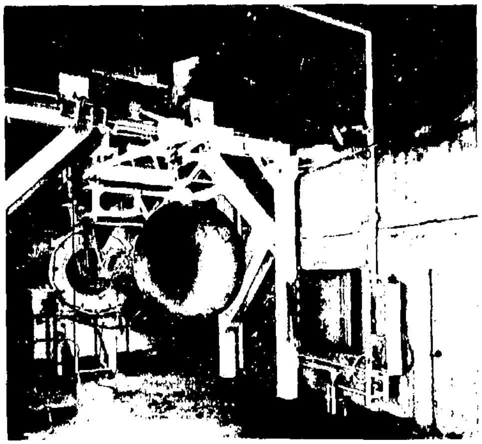
Temperatures were measured as follows:

- o Combustor inlet - Chromel-Alumel thermocouples (289 to 1637 K)
- o Combustor discharge - platinum/platinum-10-percent rhodium thermocouples (255 to 1922 K)

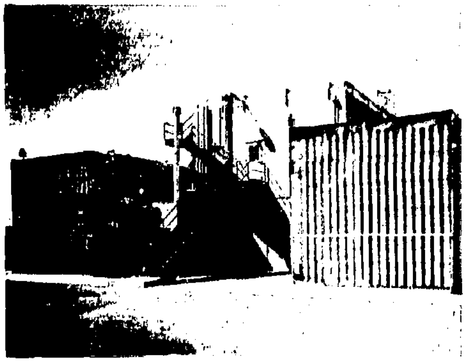
Inlet air humidity was measured at the start of each test with a Beckman electrolytic hygrometer. Liquid fuel flow was measured with five rotometers that have a total range of 2 to 450 kg/hr. Airflow was measured in accordance with standard ASME orifice-metering practice. Data were recorded both manually and automatically.

D. - ENGINE TEST FACILITY AND INSTRUMENTATION

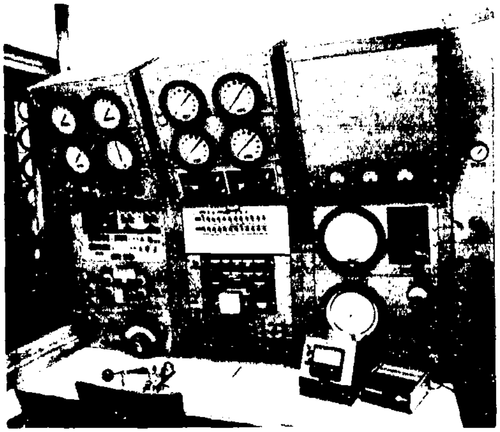
1. Facility. - The Model TFE731 engine is tested in a facility of approximately 372 square meters containing two thrust-stand cells and supporting areas. The test cells, control modules, staging areas, and a high-speed digital data acquisition system are all housed in a single structure. This test facility, shown in Figure 9, has thrust capabilities up to 22 kN and is utilized for development, qualification, and production testing of AiResearch prime propulsion turbofan engines.



TYPICAL TEST CELL



DUAL TEST FACILITY FOR
TURBOFAN/TURBOJET ENGINES



ENGINE TEST CONSOLE

DATA-ACQUISITION SYSTEM

Figure 9. Propulsion Engine Test Facility.

2. Instrumentation. - For this program, the normal Model TFE731-2 engine instrumentation was upgraded for the purpose of making measurements pertinent 'n the evaluation of the combustion system performance and emissiou levels. A listing of the instrumentation used during testing is presented in Table IX. Axial locations of the engine-mounted instrumentation are shown on the engine cross section in Figure 10. The circumferential position of the combustor inlet total pressure probes and thermocouples is shown in Figure 11.

In addition to the instrumentation listed in Table VIII, an emission sampling probe was used to measure the gaseous and particulate emissions of the engine core flow. The location of the probe is depicted in Figure 10. The probe had 24 sampling points and could be operated either in a 12- or 24-point sampling mode. A photograph of the probe is shown in Figure 12.

E. - EMISSION SAMPLING AND DATA-ACQUISITION FACILITIES

1. Emissions Sampling and Analysis Facilities and Equipment. - The AiResearch exhaust-gas emissions sampling and analysis equipment used in the program consisted of two basic types: that used for sampling gaseous emissions of NO_x, HC, CO, and CO_2; and that used to obtain the smoke number of insoluble particulates in the exhaust gas. The analyzers, together with all required calibration gases and other support equipment, were installed in the mobile units shown in Figures 13 and 14. All equipment, including plumbing and materials, conforms to EPA recommendations on exhaust emission analysis, as specified in Section 87.82 of the 1979 aircraft emission standards (Ref. 1). A schematic of the gas analyzer flow system is shown in Figure 15, and the particulate analyzer flow system schematic is shown in Figure 16. This equipment is described in the following paragraphs.

(a) Gaseous Emissions Analysis Equipment - This equipment consisted of the following analyzers, along with the refrigeration, gasifier, filtration, and pumping devices required for obtaining and processing the samples:

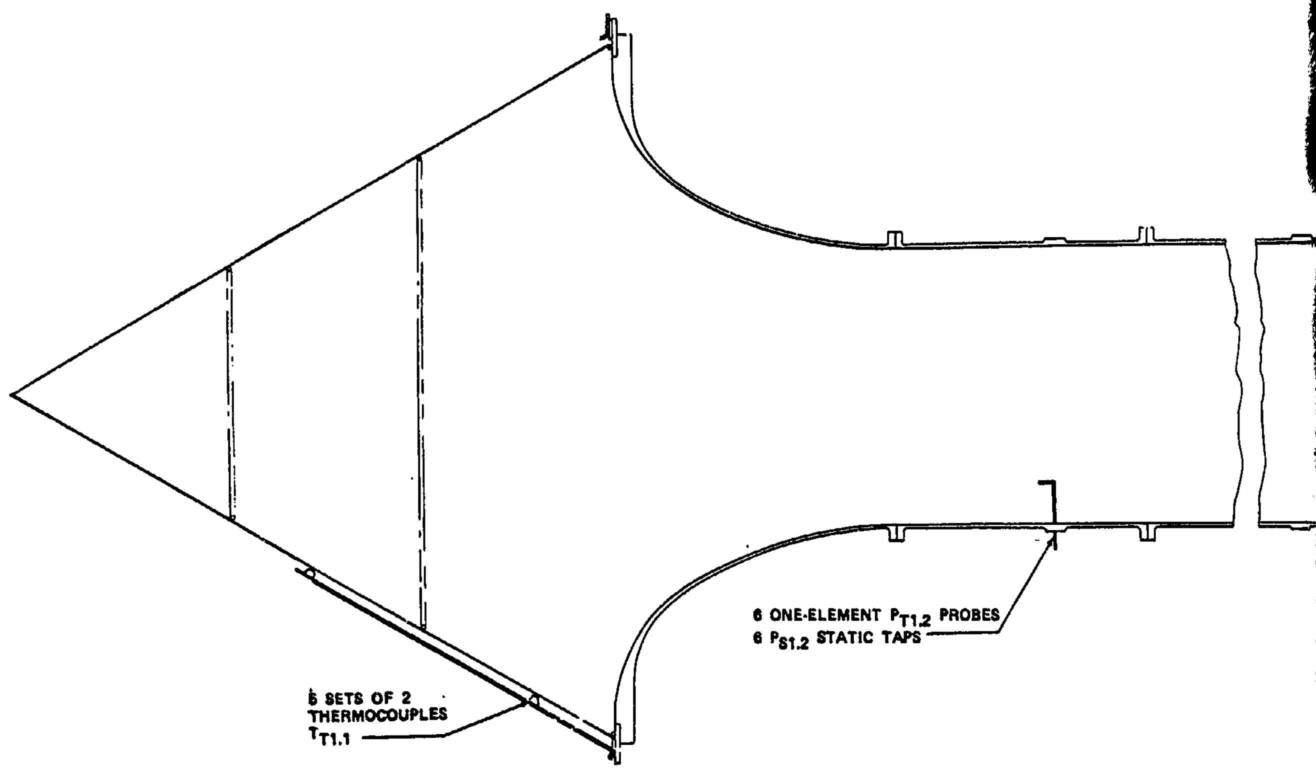
- A Thermo-Electron chemiluminescent analyzer for determining the presence of oxides of nitrogen (NO_x) over a range from 0 to 10,000 ppm

- A Beckman Model 402 hot flame-ionization-detection hydrocarbon analyzer capable of discriminating unburned hydrocarbons (HC) in the sample over a range of 5 ppm to 10 percent

- A Beckman Model 315B carbon monoxide (CO) analyzer. This analyzer has three discrete sensitivity ranges corresponding to 0 to 100, 0 to 500, and 0 to 2500 ppm.

TABLE IX. ENGINE INSTRUMENTATION.

Parameter	Symbol and Station	Unit	Engine Range	Total Req'd Recording Accuracy (Full Scale)	Sensor Type
Low rotor speed	N_1	rpm	4K-25K	±0.25%	1 monopole
High rotor speed	N_2	rpm	15K-30K	±0.5%	1 monopole
Burner plenum pressure	P_{CD}	KPa	200-1793	±0.5%	1 static tap
HPT discharge temperature	$T_{t5.0}$	K	422-1200	±5K	4 one-element probes
LPT discharge pressure	$P_{T7.0}$	kPa	103-207	±0.5%	5 five-element probes
Bellmouth total pressure	$P_{T1.2}$	kPa	90-103	±0.5%	6 one-element probes
Bellmouth static pressure	$P_{S1.2}$	kPa	90-103	±0.5%	6 static taps
Inlet screen temperature	$T_{t1.0}$	K	266-322	±2K	5 sets of 2 thermocouples
LPT discharge temperature	$T_{t7.0}$	K	394-922	±5K	5 two-element probes
LPT discharge pressure	$P_{T7.0}$	kPa	103-207	±0.5%	5 five-element probes
Primary nozzle discharge static pressure	$P_{S8.0}$	kPa	90-103	±0.5%	4 static taps
Fuel flow	W_F	kg/sec	0.024-0.376	±0.5%	2 turbine meters, 1 rotometer
Fuel pressure, primary	P_{WFP}	kPa	0-6895	±0.5%	1 transducer
Fuel pressure, secondary	P_{WFS}	kPa	0-6895	±0.5%	1 transducer
Specific gravity, fuel	FSG	-	0.7-0.9	±0.5%	
Fuel temperature	T_{FUEL}	K	283-311	±2K	1 thermocouple
Measured thrust	F_{MEAS}	kN	0-22.2	±0.5%	2 load cells
Barometric pressure	P_{BAR}	kPa	90-103	±0.5%	
Power lever angle	PLA	deg	0-120	±1°	
HPC discharge temperature	$T_{t3.0}$	K	355-755	±3K	6 one-element probes
HPC discharge pressure	$P_{T3.0}$	kPa	200-1793	±0.5%	6 one-element probes



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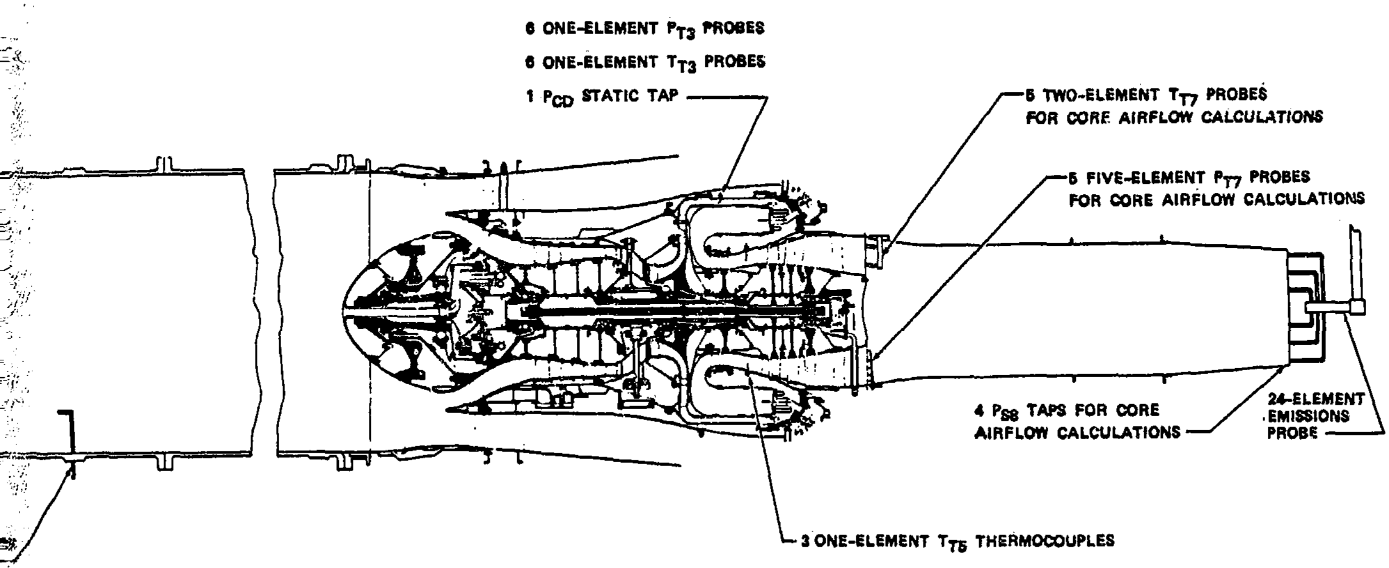

Figure 10. TFE731-2 Engine Cross Section, Showing Test-Cell Inlet and Exhaust Hardware and Test Instrumentation Locations.

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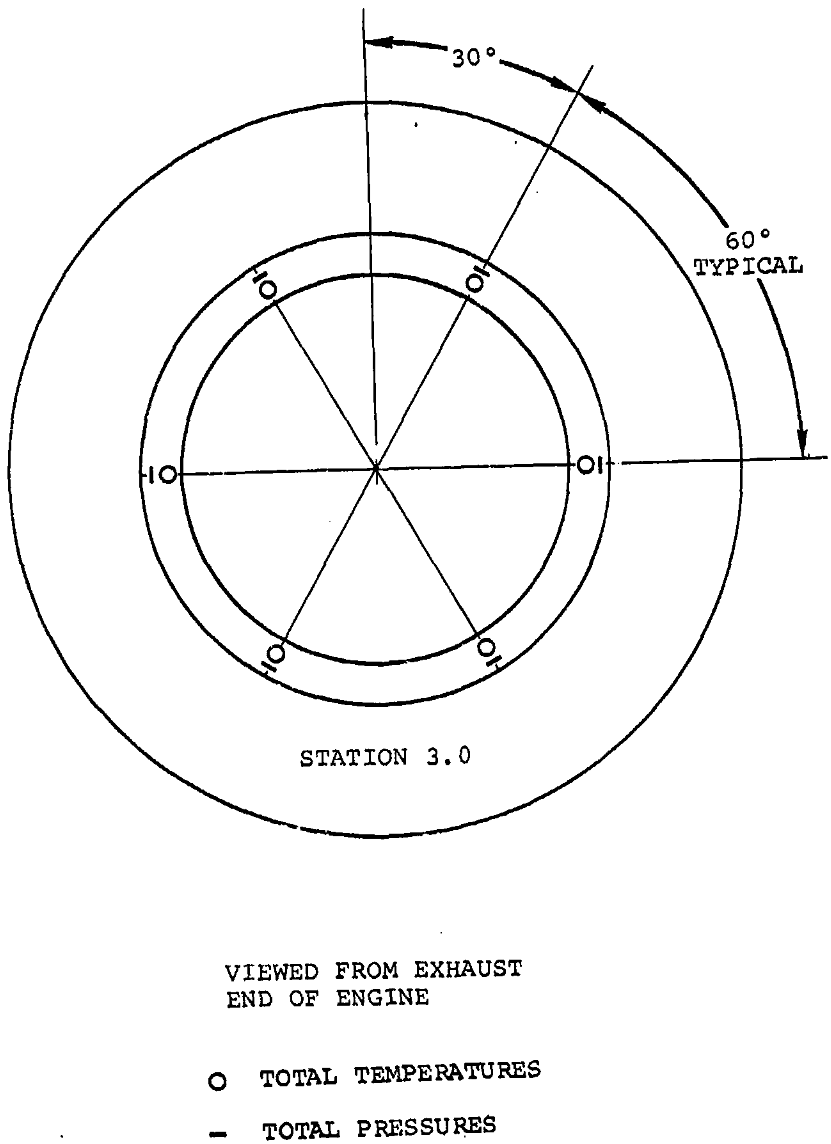


Figure 11. Circumferential Location of Combustor Inlet Instrumentation.

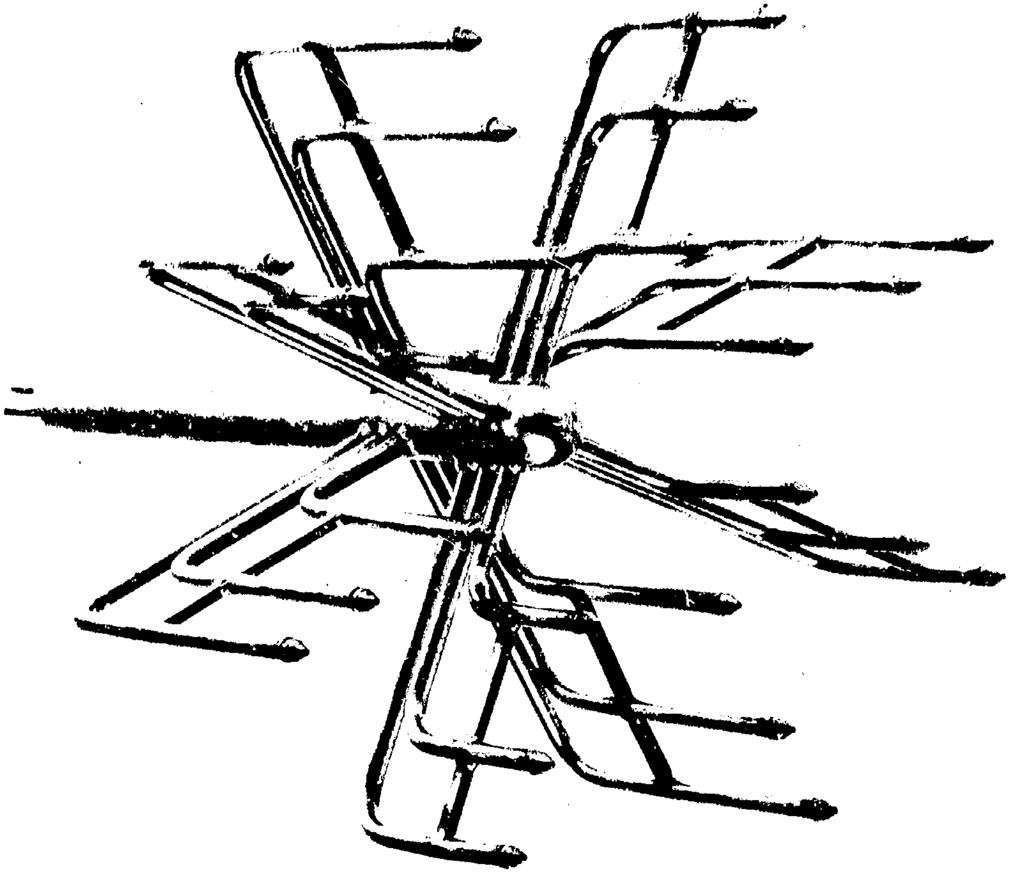
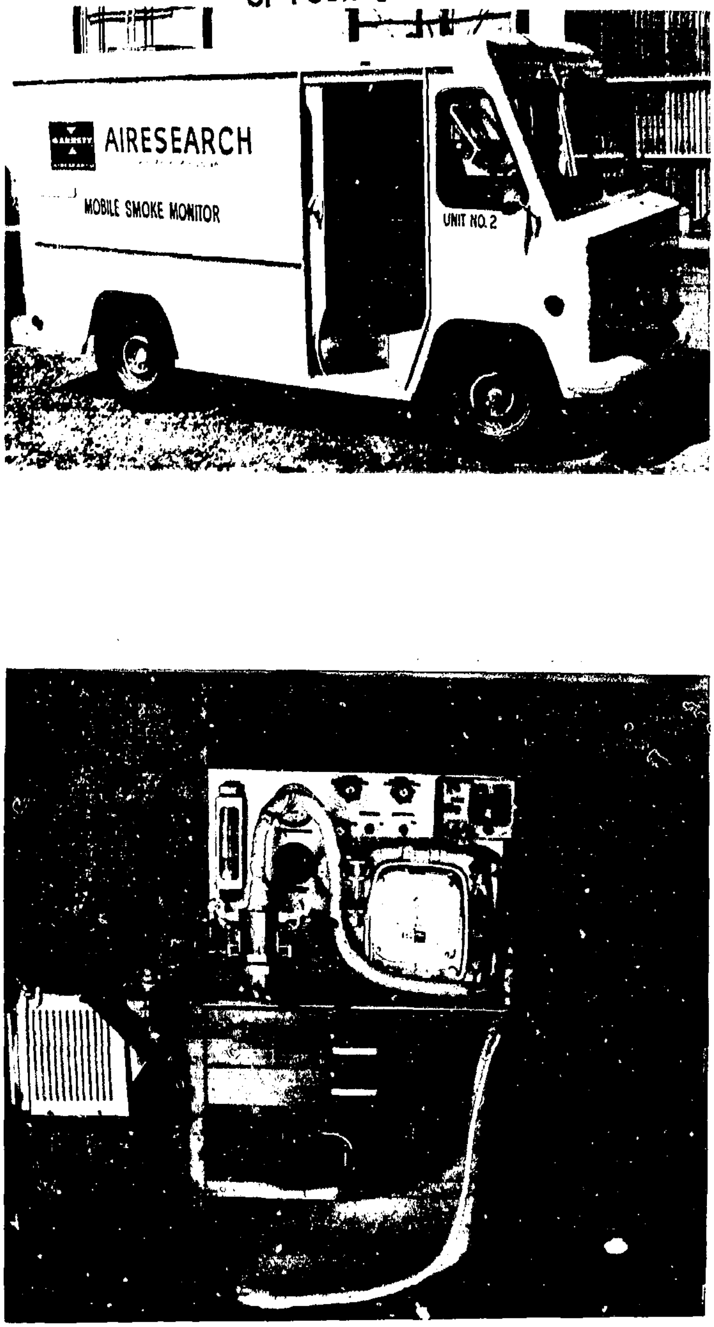


Figure 12. Emissions Sampling Probe.

GAS MEASURED	INSTRUMENT
OXIDES OF NITROGEN	CHEMILUMINESCENT ANALYZER
HYDROCARBONS	FLAME IONIZATION DETECTOR
CARBON MONOXIDE CARBON DIOXIDE	NON-DISPERSIVE INFRARED ANALYZER

Figure 13. Gaseous Exhaust Emissions Measurement Instrumentation.

KP-43879



MP-43861

Figure 14. Mobile Smoke Analyzer.

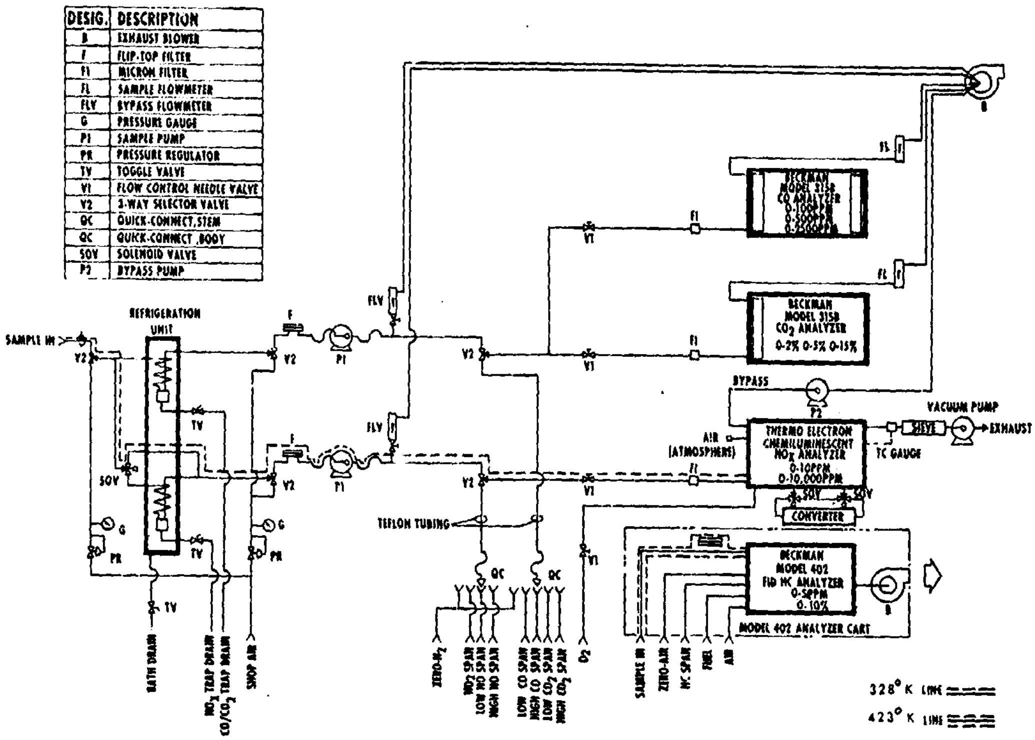


Figure 15. Exhaust Gas Analyzer Flow System.

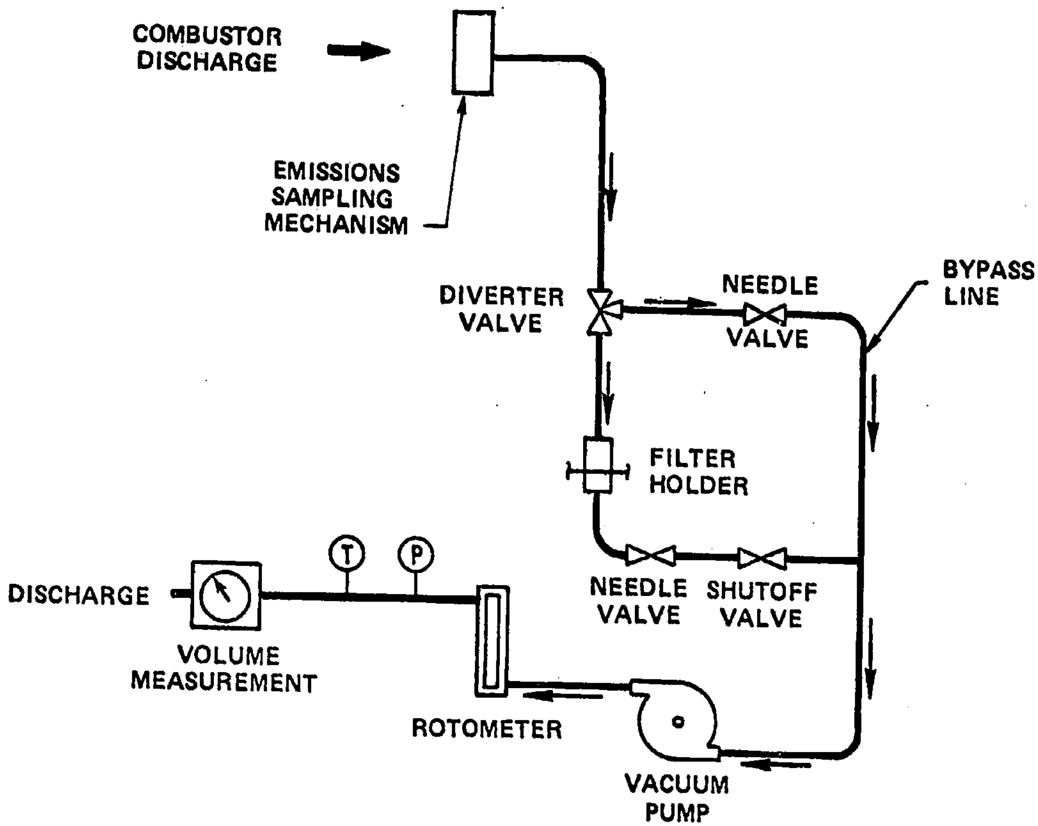


Figure 16. Particulate Analyzer Flow System

- A Beckman Model 315B carbon dioxide (CO_2) analyzer. The sensitivity ranges of this analyzer correspond to 0 to 2, 0 to 5, and 0 to 15 percent. (The measurement of CO_2 is not specifically required for the determination of pollutant emission rates. However, AiResearch conducts analyses of CO_2 in engine exhaust gases to provide a carbon balance with the fuel consumed as a means of checking the validity of test data).

All instruments, zero gases, and span gases are kept at a constant temperature to avoid drift. The equipment is capable of continuous monitoring of NO_x, HC, CO, and CO_2 in exhaust gases. The zero and span gases used to calibrate the instruments are given in Table X.

(b) Particulate Emissions Sampling and Analysis Equipment - Sample-size measurements were made with a Precision Scientific Wet Test Meter accurate to within ±0.005 standard cubic meter. Wet test pressure and temperature were measured within ±68 Pa and 0.50 K, respectively. Sample flow measurements were conducted with a Brooks Rotometer Model 110, accurate to within ±1.7 cm^3/min. A Duo-Seal Model 1405 vacuum pump, with a free-flow capacity of 0.57 cm^3/min and no-flow vacuum capability of 1 micron, was used. Reflectance measurements were conducted with a Welch Densichron Model 3837 photometer.

2. Data Acquisition. - Data acquisition for both rig and engine testing was performed by computer; originally, the SEL 810B and later by the PDP 11/70 which replaced it. All pressure, temperature, and emissions data were transmitted in terms of counts from the test facility to the computer where it was processed in real time and returned in engineering units to the test facility for display on cathode ray tubes (CRT).

For rig testing, a single CRT was used to monitor combustor inlet and discharge conditions (i.e., airflow, fuel flow, T_3, P_3, T_4, etc.). A sample display is shown in Figure 17, and an explanation of the symbols and units is given in Table XI. At the conclusion of a complete data scan (36 steps of the rotating rake) the CRT was used to display a summary of the scan and the required calculated values (i.e., pattern factor, emissions indexes, combustion efficiency, emission indexes, etc.). An example of a summary scan is shown in Figure 18.

In addition to the CRT displays, all data from the individual scans as well as the summary calculations were stored on magnetic tape and later printed out for a permanent record at the conclusion of each test. For transient tests, such as ignition, altitude relight and combustion stability, pertinent data were recorded manually.

TABLE X. - ZERO AND SPAN GASES

Gas	Concentration	Manufacturer
Zero Air and N_2	HC $\leq$ 1.0 ppm	Air Products
C_3H_8 in Air	6.3 ppm 52.0 ppm 105.0 ppm	Air Products
NO in N_2	16.9 ppm 46.5 ppm 109.0 ppm	Scott Research Labs
CO in N_2	65.0 ppm 250.0 ppm 440.0 ppm	Air Products Matheson Air Products
CO_2 in N_2	1.05% 1.97% 3.05%	Scott Research Labs

NASA T1 CONCEPT 2 MOD 3 TEST 1

OFFSET 08:27:47.5 RECORD 08:59:10.4

COND NO	= 2.0	PSIAV	= 27.45	TE2	870
HUM	= 800.	PTI1	= 27.8	TE3	865
ORFP	= 200	PTI2	= 28.0	TE4	890
ORFT	= 780.	PTI3	= 27.6	TE5	900
ORFDP	= 0.412	PTI4	= 28.5	TE6	910
WI	= 307.	PTIAV	= 27.975	TEAV	880
AORFP	= 56.	TI1	= 203	TEMX	910
AORFT	= 53	TI2	= 190	VREF	25.46
AORFDP	= 0.20	TI3	= 200	RNOX	100.
WA	= 2.0	TI4	= 195	NOX	15.8
ADP	= 20.	TIAV	= 197	NOXEI	2.56
WT	= 309	PSE	= 25.9	RCO	2500.
WFPP	= 35	PTE1	= 25.8	CO	702.9
WFP	= 181.	PTE2	= 25.9	COEI	69.28
WFSP	= 0.	PTE3	= 26.0	RCO2	5.
WFS	= 0.	PTE4	= 26.5	CO2	1.95
WF	= 181.	PTE5	= 26.2	RHC	500.
FAM	= 0.0098	PTE6	= 26.5	NC	147.1
PSI1	= 27.3	PTEAV	26.5	HCEI	8.288
PSI2	= 27.5	PLOSS	= 0.0527	ETAE	97.643
PSI3	= 27.1	TE1	= 846.	FAE	0.0099
PSI4	= 27.9				

Figure 17. CRT Display of Combustor Data (Sample).

TABLE XI. LEGEND FOR CRT DISPLAY.

SYMBOL	UNITS	EXPLANATION
		FIRST COLUMN
HUM	PPM	Inlet or specific humidity
ORFP	PSIA	Orifice pressure
ORFT	°F	Orifice temperature
ORFDP	PSIA	Orifice ΔP
WI	PM	Orifice flow rate, inlet airflow
AORFP	PSIA	Air-assist orifice pressure
AORFT	°F	Air-assist orifice temperature
AORFDP	PSIA	Air-assist orifice ΔP
WA	PM	Air-assist flow rate
ADP	PSIA	Difference between air-assist manifold pressure and rig inlet total pressure
WT	PM	Total airflow rate
WFPP	PSIA	Difference between primary fuel pressure and rig inlet total pressure
WFP	PHR	Primary fuel flow
WFSP	PSIA	Difference between secondary fuel pressure and rig inlet total pressure
WFS	PHR	Secondary (premix) fuel flow
WF	PHR	Total fuel flow
FAM	--	Measured fuel-air ratio
PSI1,4	PSIA	Inlet static pressures
		SECOND COLUMN
PSIAV	PSIA	Average of four inlet static pressures
PTI1	PSIA	Average of first four inlet total pressures, PTI1, PTI2, PTI3, PTI4
PTI2	PSIA	Average of second four inlet total pressures, PT21, PT22, PT23, PT24
PTI3	PSIA	Average of third four inlet total pressures, PT31, PT32, PT33, PT34
PTI4	PSIA	Average of fourth four inlet total pressures, PT41, PT42, PT43 PT44
PTIAV	PSIA	Average of all 16 inlet total pressures
TI1,4	°F	Inlet total temperature
TIAV	°F	Average of four inlet total temperature
PSE	PSIA	Discharge static pressure
PTE1,6	PSIA	Discharge total pressures - Number 1 refers to inner position
PTEAV	PSIA	Average of six discharge total pressures
PLOSS	--	Combustor total pressure loss
TEV	°F	Discharge total temperature - Number 1 refers to inner position

TABLE XI. LEGEND FOR CRT DISPLAY (CONTD).

SYMBOL	UNITS	EXPLANATION
		THIRD COLUMN
TE2,6	°F	Discharge total temperature
TEAV	°F	Average of six discharge total temperatures
TEMX	°F	Maximum of six discharge total temperatures
VREF	FPS	Combustor reference velocity
RNOX	PPM	Maximum value of selected NOX range
NOX	PPM	NOX concentration in wet exhaust gas
NOXEI	GM/KG FUEL	NOX emission index
RCO	PPM	Maximum value of selected CO range
CO	PPM	CO concentration in wet exhaust gas
COEI	GM/KG FUEL	CO emission index
RCO2	PCT	Maximum value of selected C)2 range
CO2	PCT	CO2 concentration in wet exhaust gas
RHC	PPM	Maximum value of selected HC range
HC	PPM	HC concentration in wet exhaust gas
HCEI	GM/KG FUEL	HC emission index
ETAE	--	Combustion efficiency from emissions
FAE	--	Fuel-air ratio from emissions

NASA T1 CONCEPT 2 MOD 3 TEST 1

SUMMARY OF 360 DEG ROTATION

OFFSET 08:27:47.5			START RECORD 08:33:36.1			NO. OF RECORDS 75		
WI	=	308.	TIAV	=	200.	CO	=	652.9
WA	=	2.0	PSE	=	26.0	COEI	=	54.55
WT	=	310.	PTEAV	=	26.6	CO2	=	2.33
WFP	=	181.	PLOSS	=	0.0534	HC	=	73.6
WFS	=	0	TEAV	=	885.	HCEI	=	3.513
WF	=	181.	TEMX	=	920	ETAE	=	98.409
FAM	=	0.0098	VREF	=	25.5	FAE	=	0.010
PSIAV	=	27.5	NOX	=	19.6	PF	=	0.051
PTIAV	=	28.1	NOXEI	=	2.69			

Figure 18. CRT Display of Average Values (Sample).

For engine testing, two CRT's were used. One was used to display the engine performance parameters (i.e., measured and corrected thrust, core airflow, primary and secondary fuel flows, etc.). This display was used to monitor engine performance and to set the proper power points at which emission values were measured. A sample display from this CRT is shown in Figure 19. An explanation of the symbols is given in Table XII. The second CRT displayed emission indexes and parameters calculated from the emissions data (i.e., fuel-air ratio and combustion efficiency). The CRT display was generated by the same program that was used for rig testing. The display was the same as that shown in Figure 17, except that all the rig test parameters were not recorded. The engine data, like the rig test data, were also stored on magnetic tape and printed out at the conclusion of the test. For acceleration and deceleration tests the required data were limited and were recorded manually.

F. - TEST PROCEDURE AND CONDITIONS

Testing during this phase of the program was divided into two portions; rig evaluation and engine testing.

1. Rig Tests - Two types of pressure-rig testing were performed during Phase III. The first involved checkout of the Concept 2, variable-geometry combustion system hardware that was to be used in the engine tests that followed. The engine tests comprised the main portion of the program test effort for Phase III, and the rig tests were used to ensure that the combustion system performance was compatible with the engine requirements and not with combustion system design requirements alone. A second series of rig tests were performed on Concept 3, the axially staged fuel injection combustion system. The intent of these tests was to further optimize this approach to emissions reduction.

a. Concept 2 Compatibility Tests - To ensure the compatibility of the combustion system hardware with the engine, a series of rig tests were performed. During these tests the variable-geometry actuation system also underwent a thorough checkout. These rig tests included combustor performance and emissions level evaluation, determination of ignition, altitude relight, and combustion stability data, and liner wall-temperature information.

(1) Combustor Performance and Emission Level Evaluation - These tests involved operating the combustion system at the four LTO power settings and measuring the normal combustor performance parameters and gaseous emissions levels. The two lower power settings -- taxi idle and approach -- were run at actual engine inlet and exit conditions. The climbout and takeoff points were run at 414 kPa inlet total pressure rather than the actual conditions (1301 and 1425 kPa, respectively) due to facility airflow limitations. The airflow and fuel flow rates were also scaled to maintain the proper corrected flow and fuel/air ratios. The inlet

```
OFFSET 02:13:43.53    6A    RECORD 05:35:24.55          TEST C
COND   =  9090.00      *    PS8.0   = 0.024663     *    TFUEL  =  78.3621
A4     =  13.8110      *    PS12.0  = 0.004185     *    PFUELT =  149.480
A5     =  26.1450      *    WET     =  55.0718     *    SFUELT =  150.510
LHV-TW =  18350.0      *    DRY     =  61.3746     *    ST IN  = 0.816621
SGF-TW = 0.824000      *    TT1AV   =  62.8248     *    SG PRI = 0.788088
32REFA =  32.1943      *    T1SPRD  =  9.62061     *    SG SEC = 0.799110
32REFB =  32.3473      *    TT3     =  730.355     *    WFTOT  =  1438.12
REF150 =  150.096      *    T4CALC  =  1719.25     *    WFP    =  375.141
PBARO  =  28.7007      *    TT5#1   =  1439.35     *    WFS    =  1063.80
PS1.2  = -0.971666     *    TT5#2   =  1462.85     *    WF-WFP =  1062.98
PT1.2  = -0.001757     *    TT5#3   =  1465.90     *    WF-WFS =   374.32
PS2.35 = 0.445720      *    TT5#4   =  1495.45     *    P PSID =  878.100
PCD    =  154.428      *    TT7.0   =  956.311     *    S PSID =  112.952
PT3    =  160.537      *    NL      =  19020.7     *    PRI FN = 0.632983
PT7.0  =  6.47825      *    NH      =  28601.6     *    SEC FN =  5.00476
                       *    THRST1  =  2623.41     *    TSFC   =  0546162
                       *    THRST2  =  2634.51     *    WA4    =  26.0241
                       *    FNCORR  =  2734.95     *    FAM4   = 0.015350
                       *    PCTRAT  =  78.1416
```

Figure 19. CRT Display of Engine Data (Sample).

TABLE XII. LEGEND FOR CRT DISPLAY

Symbol	Units	Explanation
COND		Test Condition Number
A4	IN^2	High Pressure (Turbine) Stator Area (Station 4)
A5	IN^2	Low Pressure (Turbine) Stator Area (Station 5)
LHV-TW	BTU/LB	Lower Heating Value of Fuel
SFG-TW	-	Specific Gravity of Fuel
32REFA	°F	Reference Junction Temprature
32REFB	°F	Reference Junction Temperature
REF150	°F	Reference Junction Temperature
PBARD	INHG	Barometric Pressure
PS1.2	PSIG	Bellmouth Static Pressure
PT1.2	PSIG	Bellmouth Total Pressure
PS2.35	PSIG	LPC Bleed Static Pressure
PCD	PSIG	Combustor Inlet Static Pressure
PT3	PSIG	Combustor Inlet Total Pressure
PT7.0	PSIG	LPT Discharge Temperature
PS8.0	PSIG	Primary Nozzle Discharge Static Pressure
PS12.0	PSIG	Fan Nozzle Discharge Static Pressure
WET	°F	Wet Bulb Temperature
DRY	°F	Dry Bulb Temperature
TT1AV	°F	Average of Ten Bellmouth Inlet Temperature
T1SPRD	°F	Spread of TT1
TT3	°F	Combustor Inlet Total Temperature
TT5#1-#4	°F	HPT Discharge Temperature
TT7.0	°F	LPT Discharge Temperature
NO	RPM	LPC Speed
NH	RPM	HPC Speed
THRST1, THRST2	LBS	Measured Thrust
FNCORR	LBS	Corrected Thrust
PCTRAT	PERCENT	Percent Rated Thrust
TFUEL	°F	Engine Inlet Fuel Temperature

TABLE XII. LEGEND FOR CRT DISPLAY (CONTD)

Symbol	Units	Explanation
PFUELT	°F	Primary Manifold Fuel Temperature
SFUELT	°F	Secondary Manifold Fuel Temperature
SG IN	-	Fuel Specific Gravity at Engine Inlet Temp.
SG PRI	-	Fuel Specific Gravity at Primary Manifold Temp.
SG SEC	-	Fuel Specific Gravity at Secondary Manifold Temp.
WFTOT	LB/HR	Total Fuel Flow (Flowmeter)
WFP	LB/HR	Primary Manifold Fuel Flow (Flowmeter)
WFS	LB/HR	Secondary Manifold Fuel Flow (Flowmeter)
WF-WFP	LB/HR	WFTOT-WFP = WFS
WF-WFS	LB/HR	WFTOT-WFS = WFP
P PSID	PSID	Primary Manifold Fuel Pressure
S PSID	PSID	Secondary Manifold Fuel Pressure
PRI FN	LB/HR PSID	Primary Manifold FLow No. per Nozzle
SEC FN	LB/HR PSID	Secondary Manifold Flow No. per Nozzle
RSFC	LB/HR/LB	Specific Fuel Consumption
WA4	LB/SEC	Engine Core Airflow
FAM4	-	Measured Fuel/Air (WFTOT/WA4)

temperatures were maintained at engine values. The rig test conditions are specified in Figure 20.

The main purpose of these tests was to determine the combustion system pressure loss and the circumferential and radial temperature distribution of the combustor discharge gases, and to compare them with the production combustion system values. The data from the Concept 2 rig tests were to be compared with data from production combustion systems before the start of Concept 2 engine testing. Emission measurements were also made to determine if there had been any degradation in emissions values from the final Phase II results. The variable-geometry system was actuated at approach and data taken at several valve positions to determine the effect on performance and emission levels.

(2) Ignition, Altitude Relight, and Combustion Stability - The purpose of these tests was to determine the ignition, altitude-relight, and combustion stability envelopes for the combustion system, and to compare them to the envelopes of the production combustion system. The test points selected represented actual engine conditions that would be encountered under normal operation.

For the ignition and altitude-relight points, the proper combustor-inlet conditions were set and a fuel flow was selected slightly below the successful production system value. The ignition system was activated and the fuel solenoid valve opened. If there was an indication of a light-off (temperature rise) within 2 seconds or less, the light-off was considered successful. If not, the fuel-flow rate was increased and the ignition attempt repeated after sufficient time had elapsed to drain any accumulated fuel from the combustor. If the original light-off was successful, the fuel flow was reduced and another light-off attempt made after the combustor discharge temperature had returned to within 2.7 K of the combustor inlet temperature. The ignition point was selected as the lowest fuel-flow rate that produced a light-off in 2 seconds or less from the time the fuel was turned on.

For the stability test, the combustor-inlet conditions were set to the proper values with the combustor operating. The fuel-flow rate was then reduced while maintaining the inlet conditions. The stability limit was determined by the fuel flow rate where burning ceased, as indicated by a rapid drop in combustor-discharge temperature.

(3) Combustor Wall Temperature Measurements - The wall temperatures of the combustion liner were determined using temperature sensitive paint that was applied over the entire combustor surface (excluding the swirlers). The combustor was installed in the rig and run at the maximum power setting (takeoff) for 10 minutes. Data scans were made during this time period to ensure

Date ____________________

C100 - COMBUSTION CELL TEST REQUEST

EWO: ______________________________ Test Title: Emission and Performance

Test Request 2 Tests - LTO Cycle Plus Cruise

Applicable Unit: TFE731-2

Combustion Chamber Liners:

1. Various 3. ____________ 5. ____________

2. ____________ 4. ____________ 6. ____________

Igniter Various Atomizer Various

Ignition Unit Various Ignition Lead Various

Cell Test Rig 3551400 Fuel ASTM D1655-73, Type Jet A

Operating Conditions:

Cond. No.	Airflow Data							Combustor Data					Remarks
	Flow, Lb/Min	Orifice Size	$\sigma\Delta P$ "H_2O	P_o PSIG	T_o °F	ΔP "H_2O	σ	T_{in} °F	P_{in} "HgA	P_{in} "Hgg	T_{disch} °F	W_{fuel} Lb/Hr	
1	171.6	8 X 6	15.8	50	110	4.0	4.0	100	59.7		1100	165	Ignition
2	305.5	8 X 6	50.5	100	220	8.5	5.9	206	59.7		898	193	Taxi-idle
3	772.0	8 X 6	328.0	200	465	40.1	8.2	448	157.0		1235	532	Approach
4	531.1	8 X 6	155.0	200	760	25.0	6.2	739	122.0		1695	469	Climbout
5	522.1	8 X 6	149.5	200	790	24.7	6.0	772	122.0		1768	482	Takeoff
6	522.1	8 X 6	149.5	200	270	14.4	10.4	250	122.0		900	350	Shutdown

Remarks:

Figure 20. Test Facility Instruction Sheet Emission and Performance Tests (Sample).

that the system was running at the proper conditions. Following the test completion, the combustor was removed from the rig and isotherm lines drawn on the combustor to denote wall-temperature values and gradients. The isothermed combustor was then photographed.

b. Concept 3 Optimization Tests - Rig testing of the Concept 3 combustion system was limited to a continuation of the development efforts that commenced during Phase II. Testing was performed only at the four LTO power-setting points, and the same test conditions were used as on the Concept 2 system checkout for performance and emissions levels (see Figure 20 for the rig test conditions). During these tests, the major parametric evaluation was the effect of fuel-flow splits between the pilot zone and the main combustion region on emissions values and pattern factor.

2. Engine Tests - Engine tests were limited to the Concept 2 design and involved two types of tests; steady-state and transient.

a. Steady-State Tests - The majority of the engine tests were done at steady-state conditions. These tests entailed performance, emissions, and liner-wall temperature evaluations. Table XIII shows the power settings that were used during steady-state testing. Each test did not involve each power setting, and wall-temperature evaluations were not made during each test. The content of each specific test was up to the discretion of the test engineer, and depended on the particular configuration and the information sought. However, a complete set of data (LTO emissions values, smoke, engine performance, and liner wall temperature) was obtained for each configuration that showed the potential of meeting program goals.

Testing was accomplished by allowing the engine to stabilize at the desired power setting, as specified by the fuel/air ratio from Table XIII. When stable operation was attained, the computer data acquisition system was activated and three scans of data were recorded. The engine was then transitioned to the next power setting and the procedure repeated. When a change in the swirler-valve setting was required, it was made at this time. When smoke data was taken, it was necessary to repeat the test points with the smoke sampling equipment connected in place of the gaseous emission sampling hardware. When a liner-wall temperature test was made, the combustor was painted with temperature-sensitive paint prior to engine assembly.

b. Transient Tests - Transient tests were limited to configurations that produced acceptable results during the steady-state test.

TABLE XIII. STEADY-STATE PERFORMANCE/EMISSION TEST POINTS.

Test Point	Sub-Idle	Idle	Rich Idle	Sub-Aprch	Aprch	Rich-Aprch	Sub-Climbout	Climbout	Takeoff
Percentage of Rated Power*	3-4	5.7	13	22	30	50	70	90	100
12-Point Emission Probe		x			x			x	x
24-Point Emission Probe	x	x	x	x	x	x	x	x	x

*Engine will be set to the fuel/air ratios that correspond to the power settings listed as calculated from the engine model. The fuel/air ratio will be calculated from measured fuel flow and airflow data.

These tests consisted of acceleration and deceleration tests and were performed to determine the transient characteristics of the engine. These tests were conducted in accordance with CFR Title 14, Federal Aviation Administration, Part 33.73, "Power or Thrust Response." In essence, this document requires that the engine be able to accelerate from not more than 15 percent to 95 percent of the rated takeoff thrust in 5 seconds. This acceleration rate was accomplished with the power lever moved from the minimum to maximum position in less than 1 second without overtemperature, surge, stall, or other detrimental factors occurring in the engine.

The engine procedure that was used for the acceleration and deceleration tests is specified below:

- <u>For Acceleration Tests</u>: The engine was operated at idle conditions for 5 minutes. The power lever was then moved to the maximum position in less than 1 second. The acceleration timing was from the initial power-lever movement to the obtaining of 95 percent of rated takeoff thrust. The goal was to achieve the acceleration in 5 seconds or less. The timing was automatically measured by an electronic timer that was started by a microswitch when the throttle was moved from the taxi-idle point, and stopped when the engine reached 95 percent of rated thrust.

- <u>For Deceleration Tests</u>: With the engine running at rated thrust, the power lever was moved to the idle position in less than 1 second. The deceleration time was measured by the same automatic timer from the initial power-lever movement at the rated thrust, to a thrust equal to the idle thrust, plus 5 percent of the difference between idle thrust and rated (takeoff) thrust. The goal for deceleration time was 7 seconds.

The variable-geometry valves were cycled manually. During the acceleration test, the valves went from closed to full open at approximately the 30-percent thrust point. Conversely, during deceleration the valves went from full open to closed at the same thrust point. Total time to cycle was less than 1 second.

G. - DATA REDUCTION AND CALCULATION PROCEDURES

The methods of reducing the rig data are discussed first followed by the engine procedures.

1. <u>Combustion Rig Data Reduction</u> - Data taken during combustion rig testing were read from a magnetic tape and reduced by a computer program using a Cyber 174 computer. The program consists of the following three subprograms: (a) combustor discharge temperature survey, (b) combustor performance, and (c)

emissions data reduction and analysis. These subprograms are described in the following sections.

a. Combustor Discharge Temperature Survey - This data-reduction subprogram takes thermocouple readings and prints the resultant temperatures in both tabular and figure (plot) forms. The subprogram can accept up to a maximum of 12 radial and 60 circumferential positions. Inoperative thermocouples may be deleted at the discretion of the operator. The temperatures recorded at each circumferential position are listed by column for each thermocouple (see Figure 21). The average, maximum, and minimum temperatures, and the temperature-spread factor are computed for each radial position and for each circumferential location. A straight overall average, and an average weighted by the areas determined by the thermocouple radial locations, are also printed. The temperature-spread factor or pattern factor is calculated using both straight and weighted-average temperatures. The average, maximum, and minimum radial temperatures are plotted as a function of their angular position (Figure 22), showing the circumferential variations. Each thermocouple is given a different symbol, and all the readings of each individual thermocouple are connected by lines.

b. Combustor Performance - The combustor performance subprogram corrects fuel rotameter flow data, calculates combustion efficiency from an enthalpy balance, and calculates the following additional parameters:

- Inlet airflow
- Measured fuel/air ratio
- Average inlet and discharge pressures and temperatures
- Combustor pressure drop
- Reference velocity
- Inlet air specific humidity
- Volumetric heat-release rate
- Combustor loading and blowout parameters

A separate performance sheet is not printed; but the performance parameters are included in the test summary sheet, to be described later.

c. Emissions Data Reduction and Analysis - The emissions data reduction subprogram takes the millivolt readings of the emission-analysis equipment and converts them into emission volumetric concentrations, emission indexes in g/kg of fuel, and EPAP's in lb/1000 lb-thrust-hr per LTO cycle. For both the emissions indexes and EPAP's, the volumetric concentrations of the pollutant species are corrected to concentrations in wet exhaust gas from a combustion process with dry air. The CO and CO_2 recordings are considered dry data because of the use of a desiccant in the sampling train. They need only be corrected for the amount of

RUN 156 PT 8 PAP22609 REV 8 77 NOZ .3 SPACERS -2 PLATE -2 RIG JP5

UNIT 321 S/N 7 TEST 560 SCAN 35

THERMOCOUPLE NO.		1	2	3	4	5	6	7	8	9	10	11	12	RADIAL VALUES-			
RADIUS, IN.		4.46	4.62	4.83	5.03	5.24	5.44	-0.00	-0.00	-0.00	-0.00	-0.00	-0.00	AVG	MAX	MIN	SPREAD
	ANGLE, DEG.																
1	0.0	1812.	1837.	1872.	1926.	1954.	1963.	0.	0.	0.	0.	0.	0.	1894.	1963.	1812.	151.
2	10.0	1896.	1885.	1862.	1829.	1804.	1784.	0.	0.	0.	0.	0.	0.	1843.	1896.	1784.	112.
3	20.0	1874.	1913.	1933.	1926.	1911.	1890.	0.	0.	0.	0.	0.	0.	1908.	1933.	1874.	59.
4	30.0	1880.	1903.	1972.	1959.	1991.	2018.	0.	0.	0.	0.	0.	0.	1945.	2018.	1880.	138.
5	40.0	1930.	1942.	1942.	1934.	1928.	1917.	0.	0.	0.	0.	0.	0.	1932.	1942.	1917.	25.
6	50.0	1849.	1920.	1979.	2024.	2038.	2026.	0.	0.	0.	0.	0.	0.	1973.	2038.	1849.	189.
7	60.0	1812.	1829.	1838.	1866.	1877.	1888.	0.	0.	0.	0.	0.	0.	1852.	1888.	1812.	76.
8	70.0	1914.	1877.	1831.	1784.	1760.	1740.	0.	0.	0.	0.	0.	0.	1818.	1914.	1740.	175.
9	80.0	1906.	1933.	1928.	1886.	1840.	1790.	0.	0.	0.	0.	0.	0.	1881.	1933.	1790.	143.
10	90.0	1793.	1849.	1880.	1899.	1888.	1871.	0.	0.	0.	0.	0.	0.	1863.	1899.	1793.	106.
11	100.0	1785.	1801.	1807.	1823.	1821.	1806.	0.	0.	0.	0.	0.	0.	1807.	1823.	1785.	38.
12	110.0	1798.	1840.	1871.	1893.	1897.	1896.	0.	0.	0.	0.	0.	0.	1866.	1897.	1798.	99.
13	120.0	1834.	1824.	1804.	1801.	1799.	1815.	0.	0.	0.	0.	0.	0.	1813.	1834.	1799.	34.
14	130.0	1986.	1951.	1909.	1842.	1784.	1714.	0.	0.	0.	0.	0.	0.	1864.	1986.	1714.	272.
15	140.0	1940.	1994.	2018.	2007.	1974.	1942.	0.	0.	0.	0.	0.	0.	1980.	2018.	1940.	78.
16	150.0	1803.	1862.	1908.	1974.	2006.	2033.	0.	0.	0.	0.	0.	0.	1931.	2033.	1803.	231.
17	160.0	1863.	1826.	1787.	1779.	1785.	1820.	0.	0.	0.	0.	0.	0.	1810.	1863.	1779.	84.
18	170.0	1908.	1913.	1885.	1831.	1790.	1754.	0.	0.	0.	0.	0.	0.	1847.	1913.	1754.	159.
19	180.0	1837.	1903.	1966.	2014.	2021.	2009.	0.	0.	0.	0.	0.	0.	1958.	2021.	1837.	184.
20	190.0	1863.	1854.	1835.	1848.	1865.	1903.	0.	0.	0.	0.	0.	0.	1861.	1903.	1835.	68.
21	200.0	1824.	1862.	1869.	1860.	1838.	1818.	0.	0.	0.	0.	0.	0.	1845.	1869.	1818.	51.
22	210.0	1709.	1747.	1777.	1834.	1871.	1908.	0.	0.	0.	0.	0.	0.	1808.	1908.	1709.	199.
23	220.0	1757.	1725.	1693.	1689.	1676.	1666.	0.	0.	0.	0.	0.	0.	1701.	1757.	1666.	91.
24	230.0	1809.	1810.	1781.	1732.	1693.	1676.	0.	0.	0.	0.	0.	0.	1750.	1810.	1676.	134.
25	240.0	1787.	1799.	1809.	1834.	1849.	1863.	0.	0.	0.	0.	[illegible]	0.	1824.	1863.	1787.	76.
26	250.0	1902.	1866.	1817.	1758.	1701.	1642.	0.	0.	0.	0.	0.	0.	1781.	1902.	1642.	260.
27	260.0	1906.	1914.	1891.	1838.	1787.	1740.	0.	0.	0.	0.	0.	0.	1846.	1914.	1740.	175.
28	270.0	1820.	1871.	1902.	1926.	1923.	1910.	0.	0.	0.	0.	0.	0.	1892.	1926.	1820.	107.
29	280.0	1845.	1831.	1817.	1837.	1868.	1919.	0.	0.	0.	0.	0.	0.	1853.	1919.	1817.	102.
30	290.0	1877.	1876.	1860.	1829.	1793.	1762.	0.	0.	0.	0.	0.	0.	1833.	1877.	1762.	115.
31	300.0	1826.	1846.	1849.	1854.	1849.	1843.	0.	0.	0.	0.	0.	0.	1845.	1854.	1826.	28.
32	310.0	1908.	1872.	1828.	1785.	1757.	1746.	0.	0.	0.	0.	0.	0.	1816.	1908.	1746.	162.
33	320.0	1920.	1949.	1953.	1919.	1866.	1809.	0.	0.	0.	0.	0.	0.	1903.	1953.	1809.	144.
34	330.0	1809.	1859.	1885.	1930.	1963.	1995.	0.	0.	0.	0.	0.	0.	1907.	1995.	1809.	187.
35	340.0	1806.	1810.	1812.	1824.	1829.	1832.	0.	0.	0.	0.	0.	0.	1819.	1832.	1806.	27.
36	350.0	1815.	1840.	1843.	1828.	1807.	1784.	0.	0.	0.	0.	0.	0.	1819.	1843.	1784.	59.

CIRCUMFER. VALUES-	1	2	3	4	5	6	7	8	9	10	11	12
AVERAGE TEMP.	1850.	1865.	1866.	1864.	1856.	1847.	0.	0.	0.	0.	0.	0.
MAXIMUM TEMP.	1986.	1994.	2018.	2024.	2038.	2033.	0.	0.	0.	0.	0.	0.
MINIMUM TEMP.	1709.	1725.	1693.	1689.	1676.	1642.	0.	0.	0.	0.	0.	0.
SPREAD, MAX-MIN	277.	268.	325.	335.	362.	391.	0.	0.	0.	0.	0.	0.
SPREAD, MAX-AVG	136.	129.	153.	160.	182.	186.	0.	0.	0.	0.	0.	0.
STANDARD DEVIATION	58.	56.	66.	78.	91.	105.	0.	0.	0.	0.	0.	0.
MAX TEMP GRADIENT	152.	132.	140.	195.	231.	255.	0.	0.	0.	0.	0.	0.
MAX TEMP GRAD/INCH	196.	164.	166.	222.	253.	269.	0.	0.	0.	0.	0.	0.
PATTERN FACTOR	.131	.122	.144	.151	.174	.179	0.000	0.000	0.000	0.000	0.000	0.000

PATTERN FACTORS BASED ON INLET TEMP OF 808.

ALL TEMPS ARE FAHRENHEIT

THERMOCOUPLE JUNCTIONS ARE PLATINUM/PLATINUM 10 RHODIUM

OVERALL VALUES BASED ON-

	STRAIGHT AVERAGE	WEIGHTED BY AREAS	INPUT AVG
AVERAGE	1858.	1858.	1850.
MAXIMUM	*****	2038.	*****
MAXIMUM	*****	2038.	*****
MINIMUM	*****	1642.	*****
TOTAL SPREAD, MAX-MIN	*****	396.	*****
AVG TO PEAK SPREAD, MAX-AVG	180.	180.	188.
PATTERN FACTOR BASED ON SINGLE AVERAGE	.171	.172	.180
PATTERN FACTOR, (T MAX - RAKE AVG) / (INPUT AVG - T INLET)	.173	.173	

Figure 21. Typical Combustor Discharge Gas Temperature Data Display, TFE731-2 Combustion Rig.

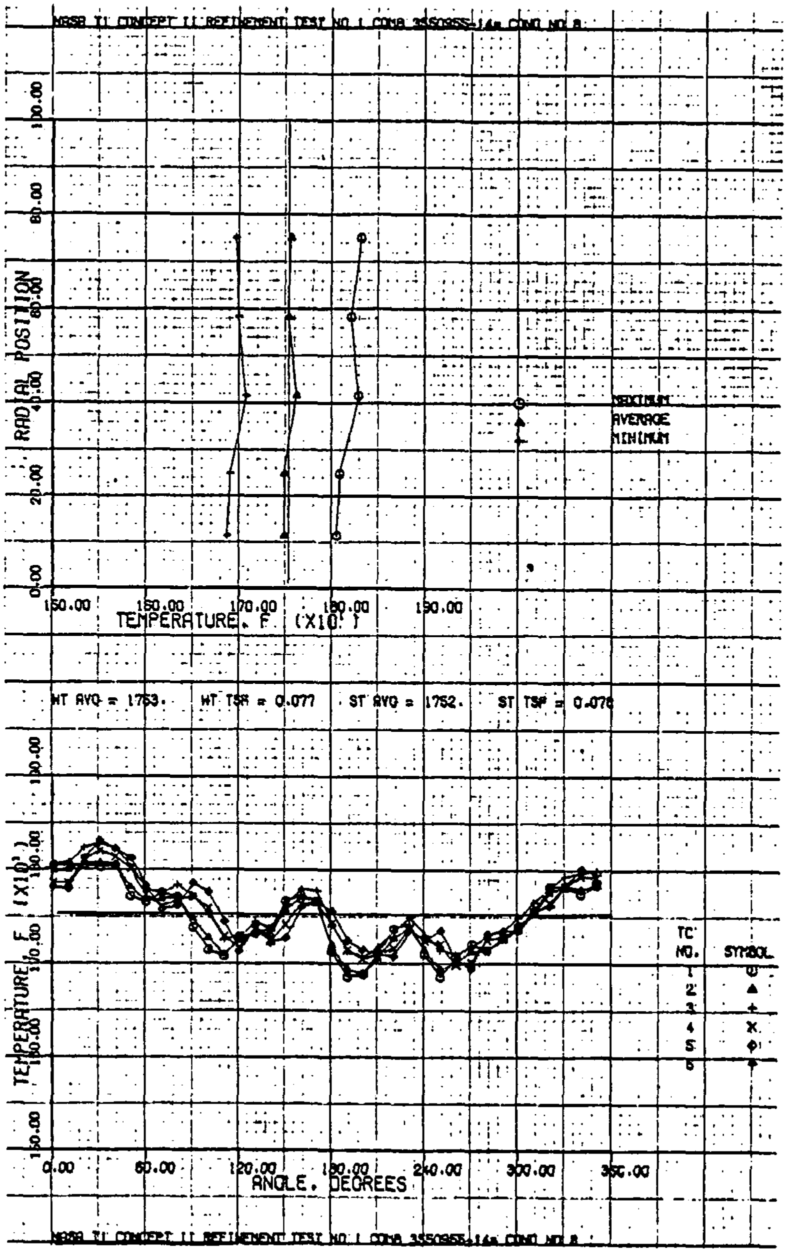


Figure 22. Circumferential Gas Temperature Variations at Turbine Inlet Section. (Sample Plot).

water vapor formed by the combustion process. The samples of HC and NO_x are not dried, and must be corrected for the initial amount of water vapor in the air to obtain the concentrations needed for the emissions indexes. In addition, since the flame ionization detection hydrocarbon analyzer is calibrated with propane, the HC concentrations are multiplied by three to convert to CH_4 concentrations. The fuel/air ratio is calculated using dry concentrations, and combustion efficiency is calculated using concentrations converted to wet exhaust gas from a combustion process with dry air (wet concentrations).

The pollutant concentrations recorded during the rotation of the emissions probe are listed by column for each specie, as typified in Figure 23. Each specie and the radially-averaged discharge temperature are also plotted as a function of their angular position (Figure 24) showing the circumferential variation. The value at any particular circumferential location is approximate, since the emission-analysis equipment response time was greater than the pause time (14 seconds) of the emission probe; however, the circumferential variation of fuel/air ratio indicates the degree of mixing of the combustion system at the exhaust plane.

d. Test Summary Sheet - The output of the above programs is a two-page summary of the test results. Included on the first page is a description of the combustor, fuel nozzles, and fuel used during the test. The first output page is typified in Figure 25. Pollutant concentrations and indexes from the emissions data-reduction subprogram are listed next for each test condition, followed by the combustor performance parameters and the average combustor-discharge temperature and pattern factor.

The second page is shown in Figure 26, and presents the emissions parameters for selected test conditions as computed for the various operating modes in the LTO cycle. HC and CO emissions are corrected by the inverse-pressure ratio between engine and rig conditions for the climbout and takeoff operating modes. Similarly, NO_x emissions are corrected using a pressure exponent for the climbout and takeoff modes. NO_x is also corrected to standard-day humidity conditions for all four LTO power settings.

2. Engine Data Reduction - The engine performance data taken during engine testing, with the exception of emissions data, were reduced by the TFE731 Quick Look Program on a PDP 11/70 digital computer. The engine-performance parameters were then written on a magnetic tape by the same program. This tape was read, along with the raw emissions data on magnetic tape, by a Cyber 174 program. This program averaged the three data scans per condition, reduced the emissions data, calculated EPA LTO cycle indexes, and printed the engine performance and emissions data together. The programs are described in the following sections.

NASA T1 CONCEPT III 3550975-3 DATA PAGE 39 COND 26-3

CONDITION NUMBER = 263 SPECIFIC HUMIDITY = .00031 LB/LB

FUEL IS AVK FUEL H/C = 1.93 STOI F/A = .06822 L H V = 18470.

CIRCUMFERENTIAL VARIATION OF EMISSIONS DATA

	EMISSION SPECIES	CO	UHC	NOX	CO2	
		PPMV	PPMC	PPMV	PERCENT	F/A RATIO
	ANGLE,DEG.					
1	0.0	174.6	6.2	1.6	1.60	.00786
2	10.0	252.6	33.9	1.2	1.20	.00595
3	20.0	319.8	56.3	.9	1.03	.00522
4	30.0	371.3	55.8	.9	1.01	.00511
5	40.0	351.2	23.7	1.0	1.17	.00588
6	50.0	255.4	8.1	1.4	1.61	.00792
7	60.0	185.4	7.8	1.6	1.66	.00813
8	70.0	186.8	12.2	1.0	.93	.00461
9	80.0	200.4	17.7	.6	.71	.00356
10	90.0	263.7	23.4	.6	.71	.00359
11	100.0	287.5	12.2	1.1	1.17	.00582
12	110.0	234.6	3.9	1.7	1.78	.00874
13	120.0	258.2	4.8	2.2	2.07	.01014
14	130.0	277.7	5.0	1.9	1.89	.00931
15	140.0	295.9	8.7	1.8	1.73	.00852
16	150.0	305.7	19.7	1.3	1.34	.00669
17	160.0	288.9	26.6	1.1	1.18	.00587
18	170.0	329.8	35.0	.9	1.05	.00530
19	180.0	365.6	35.6	.9	1.15	.00578
20	190.0	391.7	32.4	.9	1.16	.00586
21	200.0	385.9	38.9	.9	1.13	.00571
22	210.0	339.8	24.6	1.1	1.35	.00674
23	220.0	254.0	16.7	1.3	1.54	.00761
24	230.0	272.1	19.5	1.5	1.76	.00868
25	240.0	319.8	23.6	1.8	1.99	.00980
26	250.0	371.3	34.8	1.8	1.94	.00959
27	260.0	404.9	55.8	1.8	1.85	.00921
28	270.0	455.8	108.8	1.3	1.42	.00716
29	280.0	407.8	90.2	.8	.99	.00507
30	290.0	334.0	48.9	.8	.95	.00483
31	300.0	294.5	18.2	1.1	1.38	.00684
32	310.0	279.1	12.3	1.7	1.88	.00925
33	320.0	300.1	18.5	2.0	2.11	.01034
34	330.0	318.4	20.1	2.0	2.11	.01038
35	340.0	259.5	8.1	1.8	1.99	.00976
36	350.0	242.9	6.8	2.1	2.04	.01000
	AVERAGE VALUE	301.0	27.1	1.3	1.46	
	MAXIMUM VALUE	455.8	108.8	2.2	2.11	
	MINIMUM VALUE	174.6	3.9	.6	.71	
	SPREAD,MAX-MIN	281.1	104.9	1.6	1.40	
	ANGLE OF MAX VALUE	270.0	270.0	120.0	330.0	

ALL EMISSIONS CONCENTRATIONS CORRECTED TO CONCENTRATION IN WET EXHAUST FROM COMBUSTION WITH DRY AIR

UNBURNED HYDROCARBON CONCENTRATIONS GIVEN AS PPM BY VOLUME AS CARBON

EMISSION VALUES AT EACH CIRCUMFERENTIAL LOCATION ARE APPROXIMATE SINCE STEADY STATE WAS NOT REACHED

Figure 23. Emissions Survey Data (Sample).

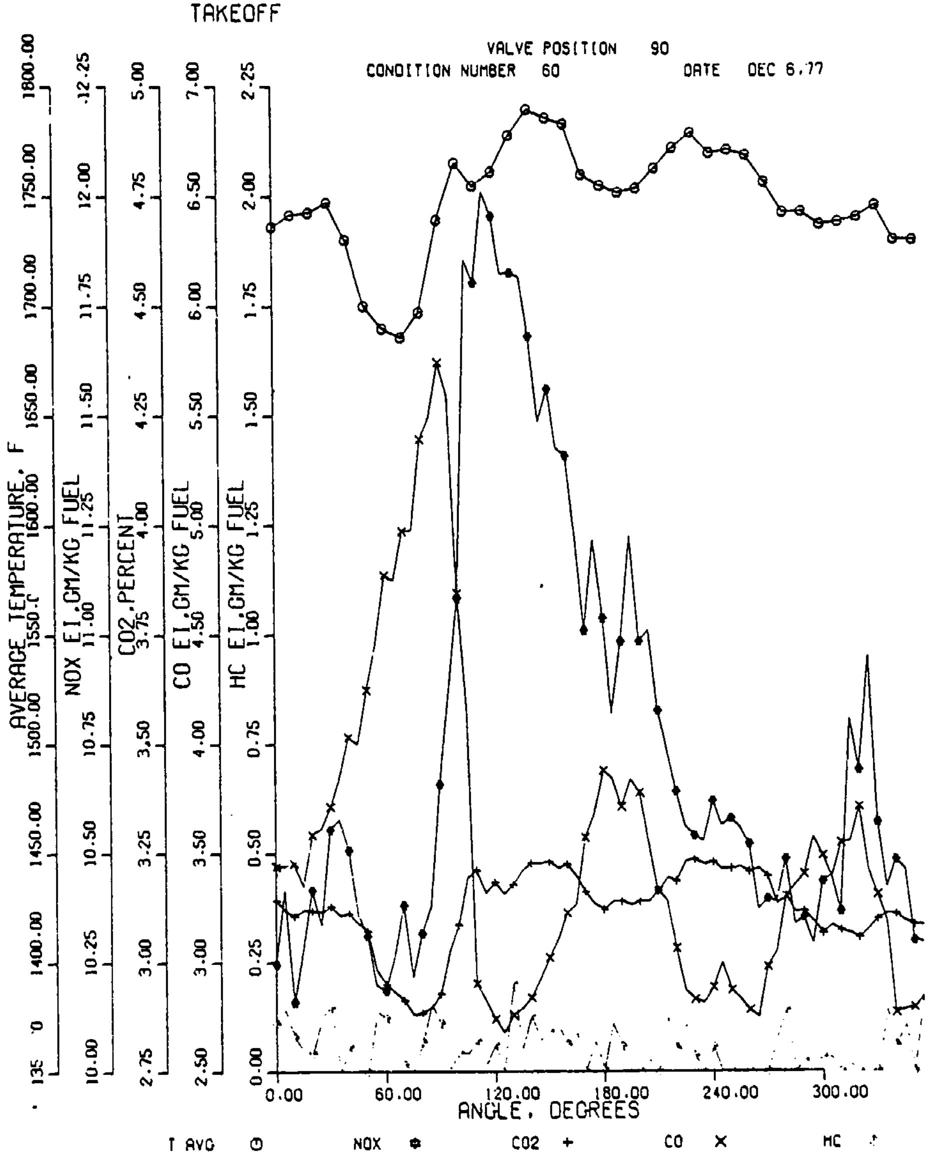


Figure 24. Typical Emissions Concentrations as a Function of Sample Probe Angular Position.

```
************************************  NASA T1 POLLUTION REDUCTION PROGRAM TEST RESULTS  ************************************
CONCEPT NO. 2  TEST  OPTIMIZATION 1          COMBUSTOR P/N   3551401-8      AIR HUMIDITY,GM H2O/KG AIR .0466    TEST DATE DEC 15,77
FUEL MANIFOLD    AIRBLAST DLN 36212                 SWIRLERS  ASSEMBLY 3551403-2 WELDED OPEN, NO LINKAGE
COMB REF AREA,IN2    253.4          COMB VOLUME,IN3  1149.0         FUEL  AVK          ATOMIC H/C RATIO     1.928           LHV,BTU/LB  18478.
                                          HUMIDITY CORRECTION FACTOR = EXP(19*(.00634-LB H2O/LB AIR))
**************************************************************************************************************************
```

CONDITION NO/VALVE POSITION	40/90	50/90	60/90
ENGINE OPERATING MODE	CRUISE	CLIMBOUT	TAKEOFF
CARBON DIOXIDE			
PERCENT BY VOLUME,WET	3.173	3.019	3.154
CARBON MONOXIDE			
PPM BY VOLUME,WET	70.642	64.895	40.343
RATE,LB/HR	2.168	2.008	1.231
GM PER KG OF FUEL	4.460	4.306	2.565
UNBURNED HYDROCARBONS- PPM AS CARBON,WEIGHTS AS CH4			
PPM BY VOLUME,WET	.267	.059	.027
RATE,LB/HR	.005	.001	.000
GM PER KG OF FUEL	.011	.002	.001
TOTAL OXIDES OF NITROGEN(NO+NO2) AS NO2			
PPM BY VOLUME,WET	66.445	66.420	75.537
RATE,LB/HR	3.349	3.376	3.785
GM PER KG OF FUEL	6.890	7.240	7.888
GM/KG FUEL,HUMIDITY CORR	6.114	6.424	6.999
SAE SMOKE NUMBER			
COMB EFFIC FROM EMISSIONS	99.894	99.899	99.940
FA RATIO FROM EMISSIONS	.01556	.01479	.01545
EQUIVALENCE RATIO,EMISSIONS	.22816	.21687	.22654
TEMP SPREAD FACTOR	.063	.053	.043
TOTAL PRESSURE LOSS,PERCENT	6.046	6.384	6.261
AIR HUMIDITY,GM H2O/KG AIR	.047	.047	.047
COMB INLET AIRFLOW,LB/SEC	8.868	9.024	8.802
INLET CORR. AIRFLOW,LB/SEC	3.325	3.454	3.396
PILOT ASSIST AIRFLOW,LB/MIN	0.000	0.000	0.000
COMB TOTAL AIRFLOW,LB/SEC	8.756	8.911	8.691
INLET TOTAL PRESSURE,PSIA	58.533	58.372	58.655
INLET STATIC PRESSURE,PSIA	57.036	56.809	57.102
DISCHRG TOTAL PRESSURE,PSIA	54.998	54.646	54.983
DISCHRG STATIC PRESSURE,PSIA	49.851	49.148	49.389
INLET TOTAL TEMP,DEG F	699.046	741.070	772.434
DISCHRG AVERAGE TEMP,DEG F	1716.005	1707.130	1786.775
COMB EFFIC FROM ENTHALPY	101.634	102.553	102.259
TOTAL FUEL FLOW,PPH	406.083	466.250	479.792
PRIMARY FUEL FLOW,PPH	486.083	466.250	479.792
PRIMARY FUEL PRESS,PSID	0.000	0.000	0.000
PRIMARY NOZZLE F/N	0.000	0.000	0.000
FA RATIO FROM MEASURED FLOWS	.01542	.01453	.01533
ASSIST AIR TEMP,DEG F	91.016	110.116	110.897
COMB REF VELOCITY,FT/SEC	37.444	39.643	39.473
HEAT RATE BTU/HR-ATM2-FT3 E6	3.445	3.344	3.415
LOADING W/P**1.75/V/E(T/540)	.13718	.12976	.11842
PILOT AIR ASSIST PRESS,PSID	0.000	0.000	0.000

Figure 25. Typical Rig Test Results Summary.

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****************************************  EPA CYCLE EMISSIONS COMPUTATION SUMMARY  ****************************************
                                          CONDITION NUMBER   2000
CONCEPT NO. 2  TEST  OPTIMIZATION .      COMBUSTOR P/N  3551431-8     AIR HUMIDITY,GM H2O/GM AIR .0000466   TEST DATE DEC 13,77
FUEL MANIFOLD    PRESSURE ATOM. PAP 23944.       SWIRLERS    ASSEMBLY P/N 3551463-2 SEALED SHUT
                                          CONDITION NUMBER   3000
CONCEPT NO. 2  TEST  OPTIMIZATION .      COMBUSTOR P/N  3551431-8     AIR HUMIDITY,GM H2O/GM AIR .0000466   TEST DATE DEC 13,77
FUEL MANIFOLD    PRESSURE ATOM. PAP 23944.       SWIRLERS    ASSEMBLY P/N 3551463-2 SEALED SHUT
                                          CONDITION NUMBER   5390
CONCEPT NO. 2  TEST  OPTIMIZATION .      COMBUSTOR P/N  3551431-8     AIR HUMIDITY,GM H2O/GM AIR .0000466   TEST DATE DEC 15,77
FUEL MANIFOLD   AIRBLAST DLN 36212           SWIRLERS  ASSEMBLY 3551463-2 WELDED OPEN, NO LINKAGE
                                          CONDITION NUMBER   6090
CONCEPT NO. 2  TEST  OPTIMIZATION .      COMBUSTOR P/N  3551431-8     AIR HUMIDITY,GM H2O/GM AIR .0000466   TEST DATE DEC 15,77
FUEL MANIFOLD   AIRBLAST DLN 36212           SWIRLERS  ASSEMBLY 3551463-2 WELDED OPEN, NO LINKAGE
      NOX CORRECTION PRESSURE EXPONENT AT CLIMBOUT =  .50.        NOX CORRECTION PRESSURE EXPONENT AT TAKEOFF =  .500
                          HUMIDITY CORRECTION FACTOR = EXP(19*(.00634-LB H2O/LB AIR))
                HC AND CO EMISSIONS CORRECTED AT CLIMBOUT AND TAKEOFF BY THE RIG TO ENGINE PRESSURE RATIO
*****************************************************************************************************************************
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MODE CONDITION NUMBER	TAXI-IDLE 2000	APPROACH 3000	CLIMBOUT 5090	TAKEOFF 6090	TOTAL PER CYCLE
TIME IN MODE,MINUTES	26.000	4.500	2.500	.500	33.500
RATED POWER,PERCENT	5.717	29.996	89.960	100.040	
THRUST,LB	200.080	1049.850	3148.610	3501.390	
LB THRUST-HR	86.701	78.739	131.192	29.178	
ACTUAL RIG PRESSURE,PSIA	28.460	76.482	58.370	58.655	
ENGINE PRESSURE,PSIA	29.319	77.137	188.658	296.633	
FUEL FLOW,LB/HR (RIG FUEL FLOW RAT. FOR SIMULATED IDLE BLEED)	192.577	532.297	1471.982	1663.127	
** HYDROCARBON EMISSIONS (HC) **					
INDEX,LB HC/1000 LB FUEL	3.886	.112	.002	.001	
INDEX,LB HC/1000 LB FUEL,CORRECTED FOR PRESSURE	3.880	.112	.001	.000	
RATE,LB HC/HR	.747	.060	.001	.000	
MASS,LB HC	.324	.034	.000	.000	.328
MASS,PERCENT OF TOTAL CYCLE	98.63	1.36	.01	.00	100.0
CYCLE,LB HC/1000 LB THRUST-HR PER CYCLE					1.008
** CARBON MONOXIDE EMISSIONS (CO) **					
INDEX,LB CO/1000 LB FUEL	42.950	4.125	4.306	2.565	
INDEX,LB CO/1000 LB FUEL,CORRECTED FOR PRESSURE	42.950	4.125	1.332	.728	
RATE,LB CO/HR	8.271	2.196	1.961	1.211	
MASS,LB CO	3.584	.165	.082	.018	3.841
MASS,PERCENT OF TOTAL CYCLE	93.32	4.29	2.13	.26	100.0
CYCLE,LB CO/1000 LB THRUST-HR PER CYCLE					11.798
** TOTAL OXIDES OF NITROGEN EMISSIONS (NOX) **					
INDEX,LB NOX/1000 LB FUEL	2.580	5.311	7.240	7.888	
INDEX,LB NOX/1000 LB FUEL,CORRECTED FOR HUMIDITY	2.289	4.712	6.424	6.999	
INDEX,LB NOX/1000 LB FUEL,CORRECTED FOR BOTH PRES. AND HUMIDITY	2.289	4.712	11.549	13.137	
RATE,LB NOX/HR	.441	2.508	17.000	21.848	
MASS,LB NOX	.191	.188	.708	.182	1.278
MASS,PERCENT OF TOTAL CYCLE	15.05	14.82	55.79	14.34	100.0
CYCLE,LB NOX/1000 LB THRUST-HR PER CYCLE					3.897

Figure 26. Typical EPA Parameter Computation Summary for Rig Tests.

a. TFE731 Quick-Look Program - This program statistically averages the raw engine data to obtain 21 engine parameters, which are listed in Table XIV. Engine performance is then calculated from the measured parameters and the input constants and curves (e.g., the primary nozzle area and curve of nozzle flow coefficient versus pressure ratio). The reduced engine data were printed for inspection as shown on a sample printout in Figure 27. The following parameters were written on tape as input to the final data-reduction program:

LPC Rotor Speed	NL
HPC Rotor Speed	NH
LPT Discharge Corrected Airflow	WATC2
Measured Thrust	FMEAS
Fuel Flow	WF
Engine Pressure Ratio	EPR
Engine Inlet Temperature	TT1
HPC Discharge Temperature	TT3
HPT Inlet Temperature	TT4-B
HPT Discharge Temperature	TT5
LPT Discharge Temperature	TT7
Engine Inlet Total Pressure	PT2
HPC Discharge Total Pressure	PT3
HPC Discharge Static Pressure	PCD
Primary Nozzle Discharge Pressure	PCD
LPT Discharge Pressure	PT7
Primary Fuel Pressure	PWFP
Secondary Fuel Pressure	PWFS
Swirler Valve Position	SVP

b. Final Data Reduction and EPAP Calculation Program - One of the functions of this program was to reduce the emissions data and, in this respect, the program was similar to the emissions subroutine of the test rig data reduction program previously described. The program differs in that the engine emissions data were taken with a fixed-averaging probe, and therefore no circumferential variations were measured. The reduced emissions data and the engine performance parameters were printed in a format similar to that shown in Figures 28 through 30.

TABLE XIV. LIST OF MEASURED ENGINE PARAMETERS.

F_{MEAS}	Measured thrust, pounds
N_1	Low rotor speed, rpm
N_2	High rotor speed, rpm
P_{BAR}	Barometric pressure, psia
P_{S12}	Fan discharge static pressure, psia
P_{S8}	Primary discharge static pressure, psia
P_{CD}	Burner plenum pressure, psia
$P_{S1.2}$	Bellmouth static pressure, psia
$P_{t1.2}$	Bellmouth total pressure, psia
P_{t2}	Engine inlet total pressure, psia
P_{t3}	HPC discharge pressure, psia
P_{t7}	LPT discharge pressure, psia
P_{t11}	Fan nozzle inlet pressure, psia
SGF	Fuel specific gravity
T_{FUEL}	Fuel temperature, °F
T_{t2}	Engine inlet total temperature, °F
$T_{t2.4}$	HPC inlet temperature, °F
T_{t3}	HPC discharge temperature, °F
T_{t5}	HPT discharge temperature, °F
T_{t7}	LPT discharge temperature, °F
T_{t11}	Fan nozzle inlet temperature, °F
WF_{CPS}	Fuel flow (turbine meter), cps

DATA POINT = 1 OFFSET RECORD TIME IS 15:23:06.5. DATA RECORD TIME IS 15:38:19. TABLES OF PHASE 3

TFE 731-3 7502-18/01 C-91 02/15/78 DEVELOPMENT 34C134F
SLED # 6

ENGINE TEST CONSTANTS

APH= 101.90	AFN= 196.00	A4 = 14.220	A5 = 27.400	SG = .81400	LHV= 18480.	DBT= 57.00	WBT= 48.000	TOL= .20000	
K1 = 4.3100	K2 = 1.6100	K3 =.001667	K4 = .9800	KC1= .00140	KC2= .00930	KC3= .01550	KC4= .00000	FGR= .55590	
EFL= .0000	N/A= .0000	N/A= .0000	N/A= .0000	N/A= .0000	ABM= 618.33	ACC= 102.86	A1 = 624.30	A2 = 172.00	

DATA ACQUISITION AVERAGE VALUES

	AVERAGES	VARIATION	% VAR.	TOT	ACC	REJ		AVERAGES	VARIATION	% VAR.	TOT	ACC	REJ
TT1 =	58.8630	.0000	1.0000	10	10	0	NL =	6415.4961	.0000	.0000	1	1	0
TT2.4 =	.0000	.0000	.0000	0	0	0	NH =	17825.4062	.0000	.0000	1	1	0
TT3 =	.0000	.0000	.0000	1	0	0	PT7EPR =	14.1572	.0000	.0000	1	1	0
TT5 =	878.3906	.0000	.0000	2	2	0	TS2.35 =	.0000	.0000	.0000	0	0	0
TT7 =	768.5586	46.7276	3.7658	10	7	3	TT2.35 =	.0000	.0000	.0000	1	0	0
TT11 =	71.4641	3.7355	.4277	20	7	12	TT9 =	.0000	.0000	.0000	0	0	0
TFUEL =	64.2493	.0000	.0000	1	1	0	TT2.2 =	.0000	.0000	.0000	0	0	0
FMEAS =	249.9518	.0300	.0000	2	2	0	TT4 =	.0000	.0000	.0000	0	0	0
WF =	.5025	.0002	.0000	1	1	0	PLA =	.0000	.0000	.0000	0	0	0
PBAR =	14.1436	.0000	.0000	1	1	0	PT9 =	.0000	.0000	.0000	0	0	0
PT2 =	14.1305	.0000	.0000	0	0	0	PT2.2 =	.0000	.0000	.0000	0	0	0
PS12 =	14.1383	.0033	.0233	4	4	0	PS2.2 =	.0000	.0000	.0000	0	0	0
PS8 =	14.2470	.2121	1.4891	4	4	0	PT2.35 =	.0000	.0000	.0000	0	0	0
PT7 =	14.4582	.0706	.2475	25	13	12	PS2.35 =	16.0069	.0000	.0000	1	1	0
PT11 =	14.6672	.0601	.1768	40	18	22	PT2.4 =	.0000	.0000	.0000	0	0	0
PCD =	29.2089	.0000	.0000	1	1	0	PT3 =	.0000	.0000	.0000	0	0	0
PT1.2 =	14.1305	.0051	.0363	6	6	0	PT5 =	.0000	.0000	.0000	0	0	0
PS1.2 =	14.0954	.0316	.2242	6	6	0	PS9 =	.0000	.0000	.0000	0	0	0
SGF =	.8123	.0000	.0000	0	0	0							

ENGINE PERFORMANCE CORRECTED TO STANDARD DAY (T AMB. = 59 DEG F, P AMB. = 14.696 PSIA)

THRUST-LBS / SPEED-RPM		TEMP DEG F		PRESS. RATIOS		FLOW-PPS ENG. COEFF.		FUEL-PPH		UNCORRECTED DATA	
FNTC2M=	261.2339	T235C2=	.0000	P2PS12=	.9994	WATC2M=	21.8018	SFCC2 =	.8164	TT4A =	904.5439
FNTC2C=	255.8284	TT3C2 =	.0000	P235P2=	.0000	WATC2C=	30.2778	PDSFC =	-4.6275	TT4B =	.0000
FNCORR=	1.2785	TT4AC2=	904.8574	PCDP2 =	2.0671	WA7C2 =	5.4383	WFC2 =	213.2754	TT4C =	1062.6426
NFC2 =	3566.8730	TT4BC2=	.0000	P7P2 =	1.0232	WA11C2=	24.8395	WFP3 =	7.0196	TT4S =	912.4873
NLC2 =	6416.3984	TT4CC2=	1062.9932	P7PS8 =	1.0152	BPR =	4.5675	WFP3C2=	7.0207	WF =	205.0344
NHC2 =	17827.4844	TT4SC2=	912.8027	P7PS12=	1.0226	CD7 =	.9334	FA4 =	.0111	NF =	3566.3711
THETA2=	.9997	TT5C2 =	878.7119	PS8P2 =	1.0079	CD11 =	.9365	ETAB =	.8615	NL =	6415.4961
SQRTTH=	.9999	TT7C2 =	768.8672	P11P12=	1.0374	CFA7 =	.8908	HPLOSS=	11.1538	NH =	17825.4062
DELTA2=	.9615	TT11C2=	71.6052	FPR =	1.0380	CFA11 =	.9178				
				EPR =	1.0019						

DEFAULT AND WARNING TABLE

CODE NO.	1	2	3	4	5	6	7	8	9	10	11	12	13	14
ACTIVATED	YES			YES						YES	YES	YES		

Figure 27. Engine Data Sample Printout.

```
**************************************** AIRESEARCH EMISSION TEST SUMMARY - PGM     77 ****************************************
ENG MFG    AIRESEARCH          TEST FACIL    PHX C-92  INSTR DESCRIP  FED.REGISTER VOL.43,NO.58,3/78 REDUCED  06/09/80  12.40.23
MODEL NO.  TFE731-2                S/N  7353-42/01-03           ENGINE TYPE(CLASS)  T1,TURBOFAN
RATED POWER    3500.0 LB. THRUST AT SEA LEVEL STANDARD DAY CONDITIONS                               TEST NO
FUEL  ASTM D1655-77T,JET A-1   ATOMIC H/C RATIO    1.928      LHV  18470. BTU/LB      ADDITIVES    NONE

                 SMOKE                          22.5  SMOKE NUMBER, MAXIMUM AT  TAKEOFF   MODE, 100 PERCENT RATED POWER
TAXI-IDLE SETTING    200.0 LB. THRUST ( 5.71  PERCENT RATED TAKEOFF POWER )

************************************************** ENGINE DESCRIPTION **************************************************
COMB TYPE  CONCEPT 2    VARIABLE GEOMETRY P/N   3551834-7          SUR/VOL  9.000  FUEL INJ TYPE   3551831-1 .7FN PRI
SWIRLERS 3551852-2 45DEG VANE          FUEL MANIFOLD   3551831-1 .7FN PRI
************************************************OPERATIONAL TEST DATA SUMMARY ******************************************
GASEOUS EMISSION TEST NO.                DATE  19,20MAY80         TIME                      BARO PRESS.   28.674 IN. HGA.
AMBIENT AIR TEMP.    80.70 DEG. F        RELATIVE HUMIDITY   27.00 PERCENT        SPECIFIC HUMIDITY   .006253 LB. H2O/LB. DRY AIR
AMBIENT AIR QUALITY    HYDROCARBONS (HC)   WT   PPMC      CARBON MONOXIDE (CO)   WT   PPMV    OXIDES OF NITROGEN (NOX)   WT   PPMV
SAMPLE LINE *** TEMP.   300.00 DEG. F.     FLOWRATE    14.16 LITERS/MIN.      TRANSPORT TIME      .70 SEC.    LENGTH    24.00 FT.
```

** COMPUTED EMISSIONS **

TEST CONDITION	2001	2002	2003	2004	2005	2006	4001	5001
CORR. POWER SETTING (STD DAY), PERCENT RATED	5.74	5.82	6.55	6.53	7.35	7.33	12.14	15.23
CORR. POWER SETTING (STD DAY), LB. THRUST	200.74	203.71	229.29	228.45	257.34	256.65	424.86	533.15
ACTUAL POWER SETTING, LB. THRUST	192.5	195.3	219.7	219.1	246.8	246.1	407.4	511.3
N1 SPEED, RPM	6322.59	6391.38	6762.96	6759.08	7125.81	7104.98	9031.65	10045.12
N2 SPEED, RPM	17909.48	17902.71	18713.95	18546.16	19147.65	19304.62	21789.08	22893.96
FUEL FLOW (MEAS.) LB./HR.	198.6	191.7	216.8	205.1	220.0	232.2	310.1	369.6
PRIMARY FUEL PRESSURE,PSID	200.24	187.04	224.73	216.12	229.80	233.01	253.99	261.24
SECONDARY(AIRBLAST) FUEL FLOW,LB/HR								
COMBUSTOR AIRFLOW,LB/SEC	4.82	5.83	5.42	6.19	8.65	8.96	6.42	32.36
METERED FUEL/AIR	.011451	.009137	.011118	.009197	.007060	.007198	.013418	.003173
ENGINE PRESSURE RATIO	1.00	1.00	1.00	1.00	1.00	1.00	1.01	1.01
COMPRESSOR INLET AIR TOTAL TEMP., DEG F	75.7	75.0	75.6	75.3	75.2	75.7	76.2	77.2
COMPRESSOR INLET AIR TOTAL PRESS., PSIA	14.08	14.08	14.08	14.08	14.08	14.08	14.08	14.08
COMPRESSOR DISCHARGE AIR TOTAL PRESS., PSIA	29.81	30.45	31.90	32.22	34.09	33.59	45.29	52.18
COMPRESSOR DISCHARGE AIR STATIC PRESS.,PSIA	28.76	29.36	30.78	31.05	32.80	32.48	43.59	50.29
COMPRESSOR DISCHARGE AIR TOTAL TEMP., DEG F	235.6	237.5	252.6	251.3	265.0	266.0	336.5	375.1
TURBINE INLET GAS TOTAL TEMP., DEG F	956.5	763.4	951.2	790.0	605.8	607.0	1228.6	674.4
TURBINE INTERSTAGE GAS TOTAL TEMP., DEG F	922.1	863.9	944.8	881.3	890.4	950.2	970.6	1015.9
EXHAUST GAS STATIC PRESSURE, PSIA	14.08	14.08	14.08	11.09	14.09	14.09	14.09	14.09
EXHAUST GAS TOTAL PRESSURE, PSIA	0.00	0.00	0.00	0.00	0.00	0.00	14.43	4.92
ENGINE EXHAUST GAS TEMP., DEG. F	831.7	780.4	835.0	784.9	782.5	845.2	820.3	826.2
EMISSION CONCENTRATION, WET ANALYSIS								
HYDROCARBON (HC AS CH4), PPMC	8.466	5.779	6.322	6.587	5.024	4.753	8.207	3.921
CARBON MONOXIDE (CO), PPMV	375.094	292.265	380.146	301.991	310.550	395.450	279.235	261.962
TOTAL OXIDES OF NITROGEN (NOX), PPMV	23.172	22.510	24.805	23.801	24.569	25.474	32.491	37.351
CARBON DIOXIDE (CO2), PERCENT BY VOL.	2.280	2.124	2.330	2.167	2.219	2.392	2.356	2.464
NITRIC OXIDE (NO), PPMV	.000	.000	.000	.000	.000	.000	.000	.000
EMISSION INDEX, LB. POLLUTANT/1000 LB. FUEL								
HYDROCARBONS (HC AS CH4)	.419	.308	.306	.344	.256	.224	.154	.181
CARBON MONOXIDE (CO)	32.472	27.240	32.219	27.577	27.696	32.642	23.513	21.111
TOTAL OXIDES OF NITROGEN (NOX AS NO2)	3.295	3.446	3.453	3.570	3.599	3.454	4.494	4.944
EMISSION RATE, LB. POLLUTANT/HR.								
HYDROCARBONS (HC AS CH4)	.083	.059	.066	.071	.056	.052	.048	.067
CARBON MONOXIDE (CO)	6.449	5.222	6.986	5.656	6.092	7.581	7.291	7.803
TOTAL OXIDES OF NITROGEN (NOX AS NO2)	.654	.661	.749	.732	.792	.802	1.394	1.827
COMBUSTION EFFICIENCY, PERCENT (EMISSIONS)	99.199	99.332	99.215	99.321	99.326	99.212	99.433	99.488
F/A (EMISSIONS,CALC)	.011307	.010492	.011552	.010712	.010971	.011865	.011628	.012157

Figure 28. Typical Engine Test Results Summary.

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***************************************** AIRESEARCH EMISSION TEST SUMMARY - PGM     77 ****************************************
ENGINE=TFE731-2              S/N=7353-42/01-03            COP? ./N= 3551834-7         TEST DATE 19,20MAY80 REDUCED 06/09/80   12.40.23.
SWIRLERS 3551852-2 45DEG VANE          FUEL MANIFOLD   3551631-1 .7FN PRI                          TEST ND
BAT THR= 3500.    RA ITT,F=   -0.    DEW PT,F= 40.       REL HUM= 27.00    SPEC HUM= .006253
FUEL H/C= 1.9280    STOI F/A= .06822       L H V= 18470.     ? LN T,F= 300.0      FLO,L/M= 14.160   SL TIM,S=   .7000
```

DATA POINT NUMBER	2001	2002	2003	2004	2005	2006	4001	5001	6001	4002
PERCENT CORR. THRUST	5.7	5.8	6.6	6.5	7.4	7.3	12.1	15.2	26.8	11.8
CORRECTED THRUST, LB	200.7	203.7	229.3	228.4	257.3	256.7	424.9	533.1	938.9	414.5
MEASURED THRUST, LB.	192.5	195.3	219.9	219.1	246.8	246.1	407.4	511.3	900.4	397.5
SHAFT SPEED, N1, RPM	6322.6	6351.4	6763.0	6759.1	7125.8	7105.0	9031.6	10045.1	12925.7	8949.3
SHAFT SPEED, N2, RPM	17909.5	17902.7	18714.0	18546.2	19147.6	19304.6	21789.1	22894.0	25213.3	21688.9
COMPRESSOR INLET TEMP.,DEG.F	75.7	75.0	75.6	75.3	75.2	75.7	76.2	77.2	76.6	76.6
COMPRESSOR DSCHG. PRES.,PSIA	28.8	29.3	30.8	31.0	32.8	32.4	43.6	50.3	73.9	43.1
COMPRESSOR DSCHG. TEMP,DEG F	235.6	237.5	252.6	251.3	265.0	266.0	336.5	375.1	483.6	333.8
TURBINE INLET TEMP., DEG.F	956.5	763.4	951.2	790.0	605.8	607.0	1228.6	674.4	1352.6	1039.5
ENGINE PRESS. RATIO	1.000	1.000	1.000	1.000	1.000	1.000	1.010	1.014	1.000	1.013
EXH GAS TOTAL PRESS.,PSIA	0.0	0.0	0.0	0.0	0.0	0.0	14.4	4.9	15.5	14.6
EXHAUST GAS TEMP., DEG.F	831.7	780.4	835.0	784.9	782.5	845.7	820.3	826.2	870.7	810.4
CORR COMP MAP FLOW, LB/SEC	4.82	5.83	5.42	6.19	8.55	8.96	6.42	32.36	12.37	7.87
FA RATIO MEASURED	.011451	.009137	.011118	.009197	.007060	.007198	.013418	.003173	.012964	.010828
MEASURED FUEL FLOW, LB/HR	198.6	191.7	216.8	205.1	220.0	232.2	310.1	369.6	577.4	306.9
FA RATIO CALC. FROM EMISSION	.011307	.010492	.011552	.010712	.010971	.011865	.011628	.012157	.013242	.011566
EQUIVALENCE RATIO	.165745	.153807	.169340	.157023	.160826	.173935	.170456	.178208	.194113	.169547
LOADING W/P**N/V/E(T/540)	.513	.597	.497	.561	.694	.732	.274	1.001	.159	.345
COMB EFFIC FROM EMISSIONS	99.1994	99.3322	99.2152	99.3211	99.3260	99.2124	99.4333	99.4875	99.6578	99.4446
****************SUMMARY OF REDUCED EMISSION DATA****************										
DRY BULB TEMP., DEG.F	72.5	72.2	72.7	72.7	72.6	72.9	73.6	73.9	73.3	73.9
WET BULB TEMP., DEG.F	57.7	57.6	57.7	57.7	57.7	57.8	57.9	58.1	57.7	58.6
SPEC.HUMID,LB.H2O/LB.DRY AIR	.007223	.007193	.007139	.007164	.007174	.007155	.007102	.007134	.007041	.007432
CARBON DIOXIDE										
PERCENT BY VOLUME, WET	2.28	2.12	2.33	2.17	2.22	2.39	2.36	2.46	2.69	2.34
PERCENT BY VOLUME, DRY	2.33	2.17	2.39	2.22	2.27	2.45	2.41	2.53	2.77	2.40
LB. CO2 PER LB. OF FUEL	3.10	3.11	3.10	3.11	3.11	3.10	3.12	3.12	3.13	3.12
WEIGHT FLOW, LB./HR.	[illegible]	596.2	672.7	637.8	684.0	720.5	966.5	1153.3	[illegible]	957.0
CARBON MONOXIDE										
PPM BY VOLUME, WET	375.1	292.3	380.1	302.0	310.6	395.4	279.2	262.0	186.9	[illegible]
PPM BY VOLUME, DRY	383.9	298.6	389.2	308.7	317.6	405.2	286.0	268.6	192.0	274.5
LB. PER 1000 LB. OF FUEL	32.472	27.240	32.219	27.577	27.696	32.642	23.513	21.111	13.842	22.688
WEIGHT FLOW, LB./HR.	6.449	5.222	6.986	5.656	6.092	7.581	7.291	7.803	7.993	6.964
UNBURNED HYDROCARBONS- PPM AS CARBON, WEIGHTS AS CH4										
PPM BY VOLUME, WET	8.5	5.8	6.3	6.6	5.0	4.8	3.2	3.9	4.5	5.1
PPM BY VOLUME, DRY	8.7	5.9	6.5	6.7	5.1	4.9	3.3	4.0	4.6	5.2
LB. PER 1000 LB. OF FUEL	.419	.308	.306	.344	.256	.224	.154	.181	.189	.247
WEIGHT FLOW, LB./HR.	.083	.059	.066	.071	.056	.052	.048	.067	.109	.076
RATIO LB HC/LB CO	.0129	.0113	.0095	.0125	.0092	.0069	.0066	.0086	[illegible]	.0109
TOTAL OXIDES OF NITROGEN (NO+NO2) AS NO2	--(NITRIC OXIDE NOT MEASURED SEPARATELY)--									
PPM BY VOLUME, WET	23.2	22.5	24.8	23.8	24.6	25.5	32.5	37.4	54.6	32.1
PPM BY VOLUME, DRY	23.7	23.0	25.4	24.3	25.1	26.1	33.3	38.3	56.1	32.9
LB. PER 1000 LB. OF FUEL	3.295	3.446	3.453	3.570	3.599	3.454	4.494	4.944	6.637	4.466
WEIGHT FLOW, LB./HR.	.654	.661	.749	.732	.792	.802	1.394	1.827	3.832	1.371

NOTES 1.ALL EMISSIONS CONCENTRATIONS CORRECTED TO CONCENTRATION IN WET OR DRY EXHAUST FROM COMBUSTION WITH DRY AIR.
2.EQUIVALENCE RATIO CALCULATED FROM CO2,CO,AND HC DATA AND FUEL COMPOSITION.
3.MASS EMISSIONS OF NO, NO2, AND NO+NO2 CALCULATED AS NO2 FROM CONCENTRATIONS WITH MOLECULAR WEIGHT OF NO2 (46.01).
4.COMBUSTION EFFICIENCY CALCULATED FROM CO,AND UHC AS VAPORIZED ORIGINAL FUEL ON LB/ LB FUEL BASIS.

Figure 29. Typical Engine Test Results Summary.

EPA CYCLE EMISSIONS COMPUTATION SUMMARY

MINIMUM EPA LTO-CYCLE PARAMETER FOR OXIDES OF NITROGEN EMISSIONS

CONCEPT NO. 2 TEST TFE731-2 7353-42/01 COMBUSTOR P/N 3551834-7 AIR HUMIDITY,GM H2O/GM AIR .0062527 TEST DATE 19,20MAY80

SWIRLERS 3551852-2 45DEG VANE FUEL MANIFG.D 3551831-1 .7FN PRI

NOX CORRECTION PRESSURE EXPONENT AT CLIMBOUT = .500 NOX CORRECTION PRESSURE EXPONENT AT TAKEOFF = .500

HUMIDITY CORRECTION FACTOR = EXP(19*(.00634-LB H2O/LB AIR))

HC AND CO EMISSION INDEX CORRECTED BY PCD MEAS./ PCD MODEL PRESSURE RATIO

MODE CONDITION NUMBER	TAXI-IDLE 2002	APPROACH 4007	CLIMBOUT 8094	TAKEOFF 9094	TOTAL PER CYCLE
TIME IN MODE,MINUTES	26.00	4.50	2.50	.50	33.50
RATED POWER,MEAS.,PERCENT	5.820	14.029	66.949	78.477	
CORRECTED NET THRUST,MEAS.,LBF.	203.709	491.017	2343.225	2746.705	
CORRECTED NET THRUST,MODEL,LBF.	200.000	1049.800	3148.600	3501.000	
1000 LB.THRUST-HR,MODEL	.08667	.07873	.13119	.02917	.32577
COMPRESSOR DISCHARGE PRESSURE,MODEL,PSIA.	29.319	77.137	188.658	206.633	
COMPRESSOR DISCHARGE PRESSURE,MEAS.,PSIA.	30.445	49.780	154.223	176.102	
COMPRESSOR DISCHARGE TEMP.,MODEL,DEG.F	206.200	448.400	738.200	772.500	
COMPRESSOR DISCHARGE TEMP.,MEAS.,DEG.F	237.502	355.440	708.746	758.509	
FUEL FLOW,MODEL,LB/HR(USED IN CYCLE CALC)	192.700	532.300	1471.900	1663.100	
FUEL FLOW,MEAS.,LB/HR	191.686	347.549	1257.133	1480.485	
FUEL/AIR RATIO (CALC. FROM EMISSIONS) AT MODE	.01049	.01148	.01462	.01538	
** HYDROCARBON EMISSIONS (HC) **					
INDEX,LB HC/1000 LB FUEL	.308	.401	.269	.184	
INDEX,LB HC/1000 LB FUEL,CORRECTED FOR PRESSURE	.319	.258	.220	.157	
RATE,LB HC/HR	.062	.138	.324	.261	
MASS,LB HC	.027	.010	.013	.002	.053
MASS,PERCENT OF TOTAL CYCLE	50.65	19.59	25.63	4.13	100.0
CYCLE,LB HC/1000 LB THRUST-HR PER CYCLE					.162
** CARBON MONOXIDE EMISSIONS (CO) **					
INDEX,LB CO/1000 LB FUEL	27.240	21.223	5.420	2.491	
INDEX,LB CO/1000 LB FUEL,CORRECTED FOR PRESSURE	28.287	13.696	4.431	2.123	
RATE,LB CO/HR	5.451	7.291	6.521	3.531	
MASS,LB CO	2.362	.547	.272	.029	3.210
MASS,PERCENT OF TOTAL CYCLE	73.58	17.03	8.47	.92	100.0
CYCLE,LB CO/1000 LB THRUST-HR PER CYCLE					9.854
** TOTAL OXIDES OF NITROGEN EMISSIONS (NOX) **					
INDEX,LB NOX/1000 LB FUEL	3.446	5.304	11.129	13.697	
INDEX,LB NOX/1000 LB FUEL,CORRECTED FOR PRESS.,TEMP.,HUMIDITY	3.179	7.886	13.007	15.218	
RATE,LB NOX/HR	.613	4.198	19.144	25.309	
MASS,LB NOX	.265	.315	.798	.211	1.589
MASS,PERCENT OF TOTAL CYCLE	16.71	19.81	50.21	13.27	100.0
CYCLE,LB NOX/1000 LB THRUST-HR PER CYCLE					4.877

** EMISSION INDEX LEVELS REQUIRED TO MEET EPA 1979 STANDARDS FOR CLASS T1 ENGINES **

EPA LTO-CYCLE

POLLUTANT	LBP/1000 LB THRUST-HR-CYCLE
CO	9.4
HC	1.6
NOX	3.7

REQUIRED EMISSION INDEX, LBP/1000 LB FUEL

POLLUTANT (MODE)	A	B
CO (IDLE)	27.0	26.5
HC (IDLE)	3.2	5.9
NOX (TAKEOFF)	11.5	9.4

A ASSUMES PROPORTIONAL REDUCTION OF POLLUTANT EMISSION INDEX AT EACH LTO CYCLE MODE

B ASSUMES (1) REQUIRED REDUCTION IN CO AND HC OBTAINED BY LOWERING EMISSION INDEX VALUES AT TAXI-IDLE MODE ONLY, CO AND HC EMISSIONS AT OTHER MODES REMAIN UNCHANGED, (2) REQUIRED REDUCTION IN NOX OBTAINED BY LOWERING EMISSION INDEX VALUES AT CLIMBOUT AND TAKEOFF MODES IN

Figure 30. Typical Engine Test Results Summary.

The EPA emissions standards are expressed in terms of a parameter that integrates the emissions rates at the engine idle, approach, climbout, and takeoff operating modes over a specific landing and takeoff cycle. The equation used to calculate the EPAP is exactly that specified in the EPA emissions standards (Ref. 1) for Class T1 engines. The following expression, in terms of the emissions indexes (EI) at each mode, was used to calculate the EPA parameters for HC, CO, and NO_x:

$$EPAP = 0.26511\ EI_{taxi\text{-}idle} + 0.12252\ EI_{approach} + 0.18823\ EI_{climbout} + 0.04253\ EI_{takeoff}$$

The program produced curves of the combustor pressure and temperature and the three pollutant indexes versus measured fuel/air ratio. The EI at each mode was known at the model engine, standard-day values of fuel/air ratio. The indexes were then corrected using the pressures and temperatures at the standard values of fuel/air ratio. The following expression was used to correct the HC and CO indexes from the engine data for pressures different than the standard.

$$EI_{CORR.} = EI_{MEAS.} \frac{P_{T3\ MEAS.}}{P_{T3\ STD.}}$$

where:

EI = Emissions index of CO or HC for use in EPAP calculation

P_{T3} = Combustor inlet total pressure, kPa

The NO_x emissions indexes from the engine data were corrected as follows for the effects of inlet pressure, temperature, and humidity.

$$EI_{CORR.} = EI_{MEAS.} \left(\frac{P_{T3\ STD.}}{P_{T3\ MEAS.}}\right)^{\eta} e^{(T_{T3\ STD.} - T_{T3\ MEAS.})/288}\ e^{19(H_{MEAS.} - H_{STD.})}$$

where:

EI = Emissions index of NO_x for use in EPAP calculation

P_{T3} = Inlet total pressure, kPa

T_{T3} = Inlet total temperature, °K

H = Inlet specific humidity, g H_2O/g air

H_{STD} = 0.00634 g H_2O/g air

η = Pressure-correction exponent

The pressure-correction exponent was input as 0.5. The standard-day conditions are given in Table XV.

TABLE XV. MODEL TFE731-2 ENGINE DESIGN DATA, SEA-LEVEL STATIC, STANDARD-DAY CONDITIONS.

Engine Mode	Net Thrust, kN	Fuel Flow kg/hr	Combustor Inlet Total Temp., K	Combustor Inlet Total Press., kPa	Combustor Fuel/Air Ratio
Taxi-idle	0.9	87.3	369.9	202.1	0.0105
Approach	4.7	241.4	504.5	531.8	0.0115
Climbout	14.0	667.6	665.9	1301	0.0147
Takeoff	15.6	754.3	684.6	1425	0.0154

CHAPTER III

RESULTS AND DISCUSSION

A. - INITIAL COMBUSTOR CONFIGURATIONS

Two combustion system concepts underwent test evaluation during Phase III of the program. The two combustion systems are referred to as Concept 2 and Concept 3 to be consistent with hardware nomenclature from Phases I and II.

Concept 2, shown in Figure 31, used variable geometry as a means of controlling emissions. The airflow through each of the 20 equally spaced dome air swirlers was controlled by a butterfly valve whose housing had been brazed to the swirler. The valves were adjusted to maintain the proper primary-zone equivalence ratio to minimize emissions levels at each specific power setting. Fuel was injected into the combustor through 20 piloted airblast fuel nozzles located in the center of the dome swirlers. The pilot nozzles were simplex pressure atomizers. The remainder of the combustor was conventional in design with stacked wall panels, film cooling of the liner walls, and plunged primary and dilution orifices.

Concept 3, shown in Figure 32, used axially staged fuel injection as the method of emission control. Twenty piloted airblast fuel injectors were used to fuel the pilot zone, which occupied approximately 43 percent, by volume, of the combustor. This fuel was injected axially. Forty air-assisted pressure atomizers were used to fuel the main combustion region, located downstream and adjacent to the pilot zone. This fuel was injected radially through the liner outer wall at 40 equally spaced locations around the circumference. The pilot zone operated at all power settings and was designed with a rich equivalence ratio to produce minimum emissions at taxi-idle. The main combustion zone began operation prior to the approach power point and was designed to operate with a lean equivalence ratio for low NO_x levels at the high power settings. The system was designed such that the hot gases exiting the pilot zone acted as an ignition source for the main combustion region.

1. Concept 2 - The Concept 2 design for Phase III was based on the configuration that produced the best overall emissions and combustion performance results during Phase II. This was the Optimization Test No. 1 configuration as designated during Phase II. This design, when rig and engine tested in Phase II, produced the following emissions results:

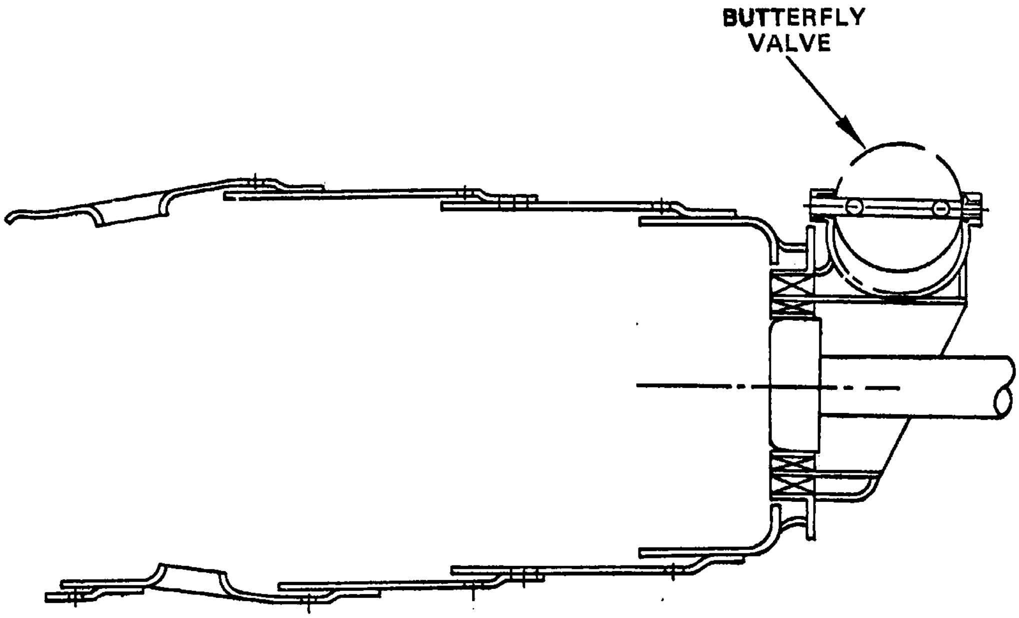

Figure 31. Concept 2 Combustor Configuration.

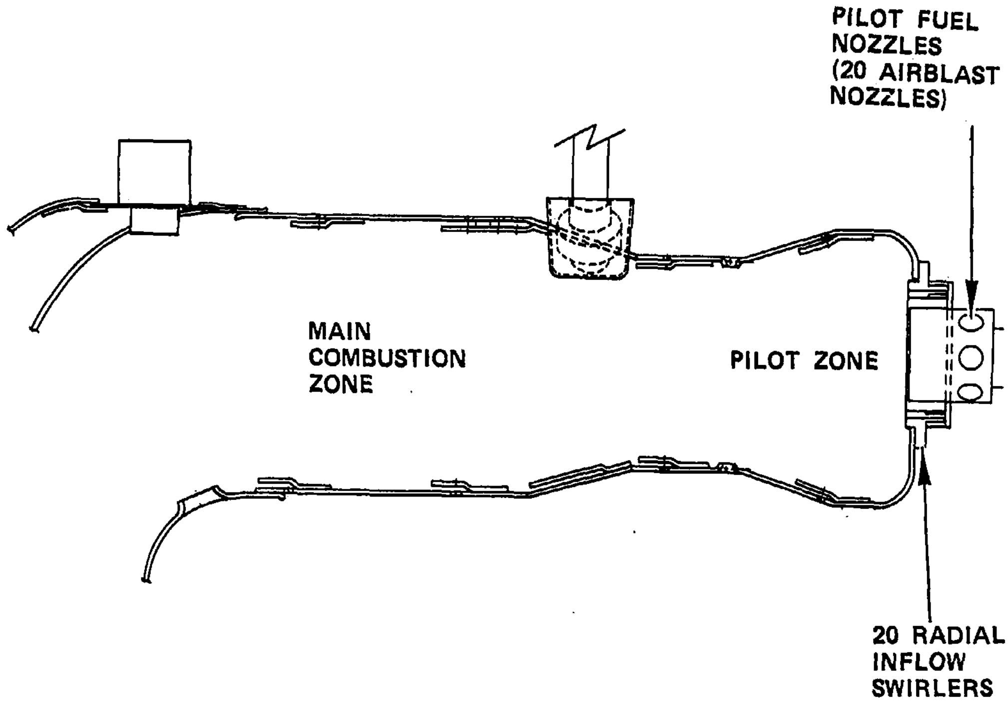

Figure 32. Concept 3 Combustor Configuration.

Type of Test	Taxi-Idle EI HC g/kg fuel	Taxi-Idle EI CO g/kg fuel	Takeoff EI NO_x g/kg fuel
Rig Test**	3.9	42.9	6.8
Engine Test**	3.4	22.2	11.5
Program Goals	6.0	30.0	7.0, 10.0*

*NO_x goal of 7.0 for rig inlet conditions and 10.0 for engine conditions.

**Airblast nozzles used at takeoff and pressure atomizer used at taxi-idle.

The engine test data indicated that the design met the HC and CO goals but was high on NO_x. The Phase III design philosophy was to leave the taxi-idle combustor configuration unchanged, but to increase the capacity of the swirlers that had airflow controlled by the valves. This was done to produce a leaner reaction zone at takeoff and climbout in order to lower the NO_x levels. Therefore, the Phase III combustion liner was identical to the Phase II Optimization Test No. 1 configuration. The system design changes were in the swirler-valve assemblies and in the fuel-nozzle design.

The swirler for the Phase III system was redesigned. The inner portion of the counterrotating double swirler was identical to the Phase II design. This kept the aerodynamics the same as for Phase II hardware. However, the outer diameter of the outer swirler was increased until it was approximately equal to the channel height of the combustor, which was the limiting constraint.

It was discovered during Phase II that small amounts of leakage through the variable-geometry valves at taxi-idle operation produced dramatic increases in HC and CO levels, and that the successful tests were accomplished when the valves were sealed with a high-temperature silicone rubber material. However, this prevented the cycling of the valves and limited testing. To evaluate high-power points required the rig be disassembled, the sealant removed, and the valves manually set to the open position.

The Phase III variable-geometry valve assembly consisted of a new design that permitted positive sealing. The assembly incorporated a butterfly arrangement that utilized a piston ring seal. The swirler-valve assembly is shown in Figure 33. Twenty of these assemblies were attached to the combustor dome, as shown in Figure 34. The individual valves were connected through linkages to a unison ring that was translated by a hydraulic actuator using jet fuel as the working fluid. The hot-end assembly with the

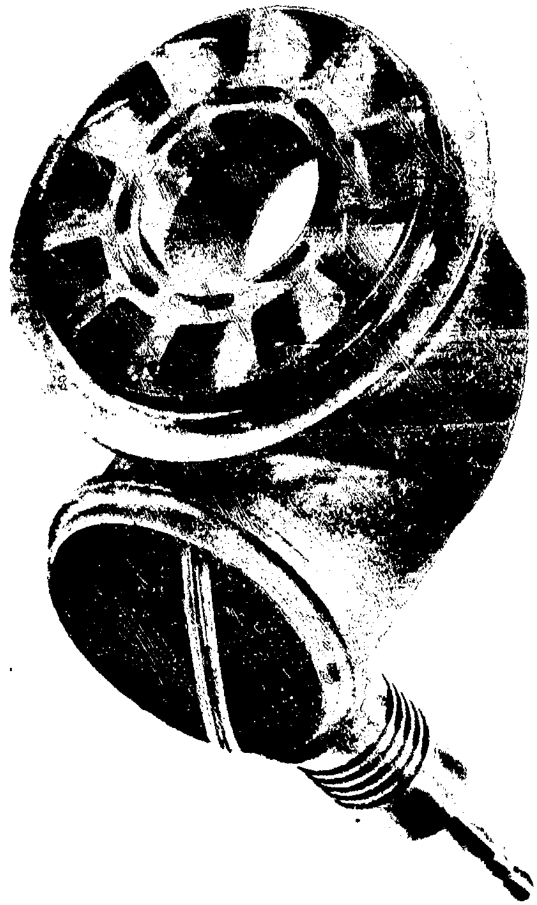

Figure 33. Valve Housing Assembly.

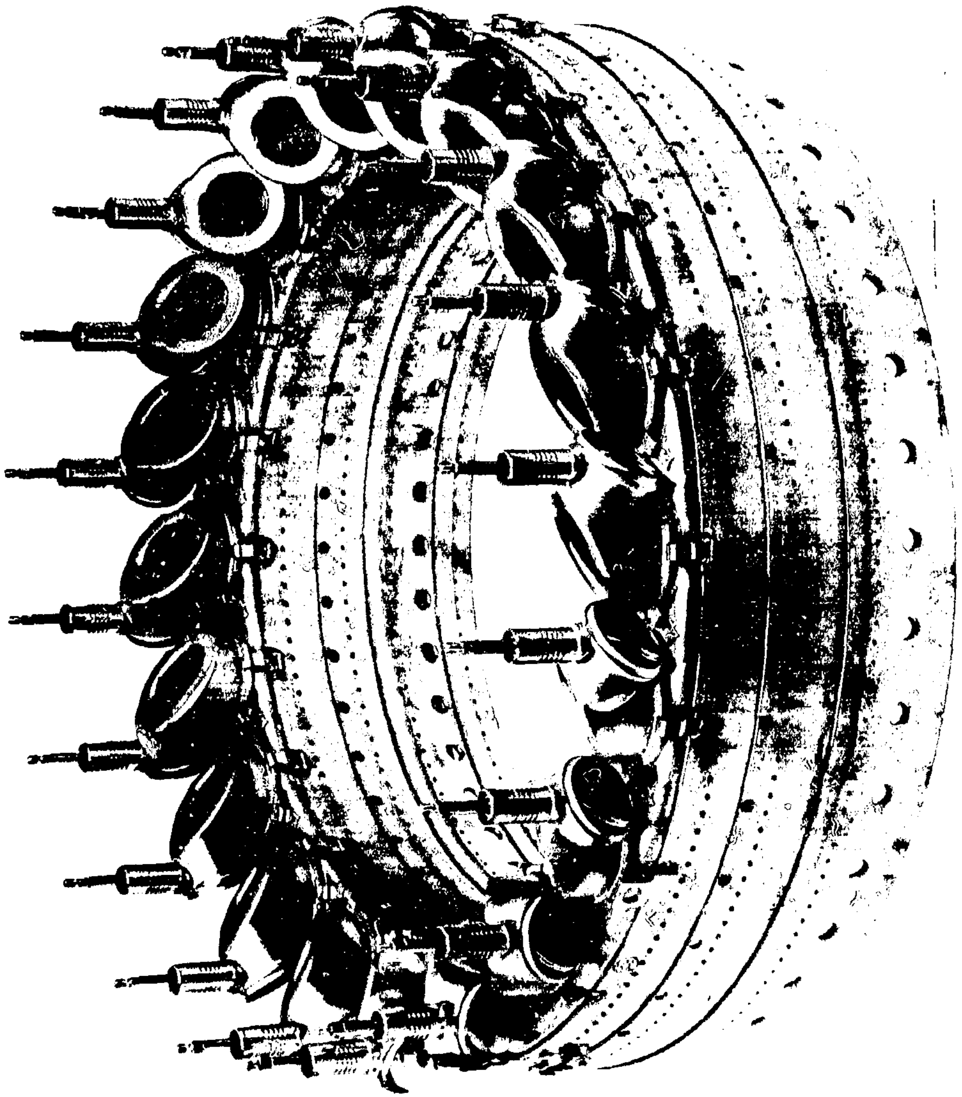

Figure 34. Combustor and Valve Assembly.

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unison ring and actuator is shown in Figure 35. An electronic control unit was used to precisely set the valves at positions ranging from closed to fully open.

Two different sets of fuel injectors were used during the Phase II engine test of the Optimization Test No. 1 configuration. At the taxi-idle point, pressure atomizers with a flow number* of 1.0 were used. Airblast fuel injectors were utilized at the higher power settings. This combination of fuel injection gave the lowest emission levels; therefore, for Phase III a piloted-airblast fuel-injector configuration was designed and developed by Delevan Manufacturing Inc. and supplied to AiResearch for testing. The pilot nozzles consisted of 0.7 flow number pressure atomizers that were integrally mounted in the bodies that housed the air-blast nozzles. Each injector had separate fuel lines for the pilot and the airblast. A standard Model TFE731 flow-divider valve was used to regulate the flow split; however, the valve was modified with a bypass loop to allow for variations in the valve crack point. A photograph of one of the piloted airblast injectors is shown in Figure 36.

2. Concept 3 - The design of the staged combustor was based on the development tests of the Phase II premix combustor. The pilot zone, located immediately upstream of the main combustion zone, was swirl stabilized and utilized 20 air-assisted airblast nozzles inserted through the combustor dome. The swirler used for all testing was a radial-flow design, which gave the strongest ignition source for the main combustion zone in Phase II. The pilot nozzles used for the initial test configuration gave the highest efficiency at taxi-idle in Phase II. The pilot zone utilized a high equivalence ratio at taxi-idle to minimize HC and CO emissions. At higher power settings, the pilot-zone equivalence ratio was reduced as much as possible to minimize NO_x emissions and still maintain an adequate ignition source for the main combustion zone. The pilot-zone volume was increased to 13 percent over the Phase II design by enlargement of the primary-zone channel height. This was done to provide an increased residence time to minimize CO and HC emissions at idle.

At high-power conditions, the main-zone fuel was injected directly into the combustor immediately downstream of the pilot zone by means of 40 air-assisted pressure atomizers. Each fuel nozzle was inserted through a tube; the 40 tubes injected 24 percent of the inlet air into the main zone to provide a lean reaction zone to minimize NO_x emissions. This design differed significantly from the Phase II premix combustor, where the main fuel was injected into an annular passage with simplex atomizers. The annulus was connected to 40 chutes that introduced the fuel-air mixture into the combustor at the same location as the Phase III main fuel nozzles. The premixing annulus was eliminated because the Phase II results showed little premixing was occurring in the

*Fuel Flow in PPH/$\sqrt{\text{Fuel Pressure in PSID}}$

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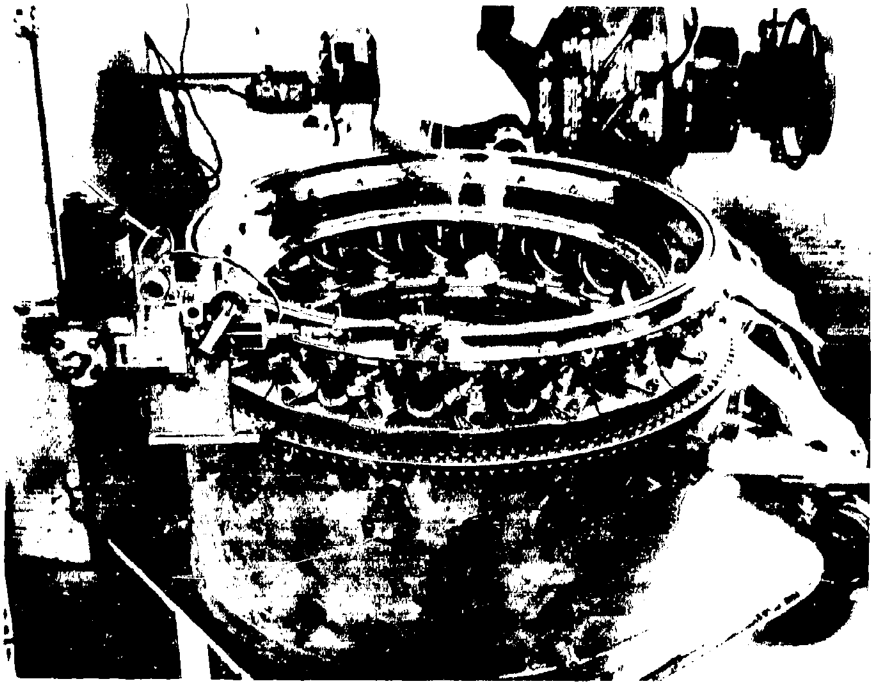

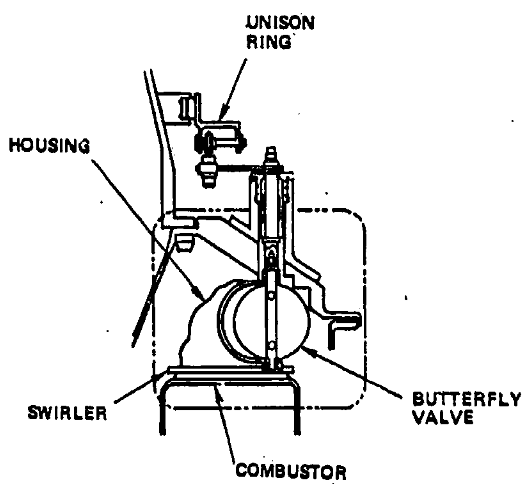

Figure 35. Combustor Valve Actuation System.

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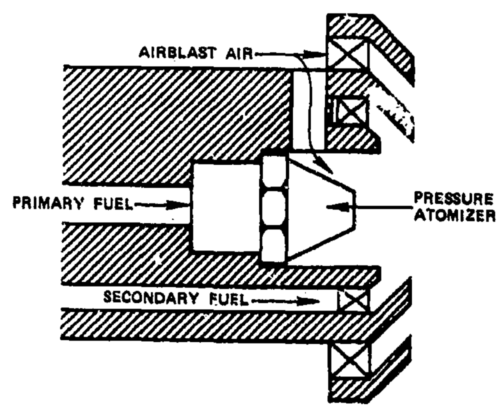

SCHEMATIC OF TIP DESIGN

Figure 36. Fuel Nozzle, Part 3551831.

annulus. Also, eliminating the annulus and chutes simplified the combustor construction and precluded flashback within the chutes. The Phase II and III initial configurations are compared in Figure 37.

B. - COMBUSTION RIG TESTS

The original intent of the Concept 2 rig testing was to check out the hardware that was to be used in engine testing. However, difficulties with the fuel-nozzle performance and sealing of the dome swirlers to the combustor necessitated a short development program prior to the system being acceptable for engine testing. The Concept 2 design approved for engine tests produced a simulated takeoff NO_x level of 7.4 g/kg fuel. At the taxi-idle condition, the HC and CO values were 18.2 and 40.5 g/kg fuel, respectively. All three of these values exceeded the program goals. However, as a result of difficulties encountered in data correlation between rig and engine testing, it was decided to proceed to engine testing at this point. A subsequent taxi-idle rig test of a further modified design produced HC and CO values of 3.2 and 21.9 g/kg fuel, respectively, which meet the program goals.

The Concept 3 staged combustion system produced NO_x levels at takeoff below the program goals (but higher than Phase II results) while maintaining a combustion efficiency equivalent to that of the production system. High efficiencies were also achieved at the taxi-idle condition without the use of air assist, and at the approach condition by minimizing the main-stage fuel flow. Smoke emissions at approach and climbout were well below the visible limit, but could only be measured at reduced pressure at the climbout condition.

The emissions results for the best overall configuration are tabulated below for both concepts. The program rig-test goals are also shown for comparison:

Concept	Taxi-Idle EI HC g/kg fuel	Taxi-Idle EI CO g/kg fuel	Takeoff EI NO_x g/kg fuel
Concept 2*	3.2	21.9	6.5
Concept 3	1.5	25.3	5.1
Program Goals	6.0	30.0	7.0

*Taxi-idle data from 8-10-79 test, takeoff data from same combustor with a different fuel nozzle design tested on 3-23-79.

1. <u>Concept 2 - Configurations and Emission Results</u> - During this phase, eight rig tests were performed on Phase III hardware,

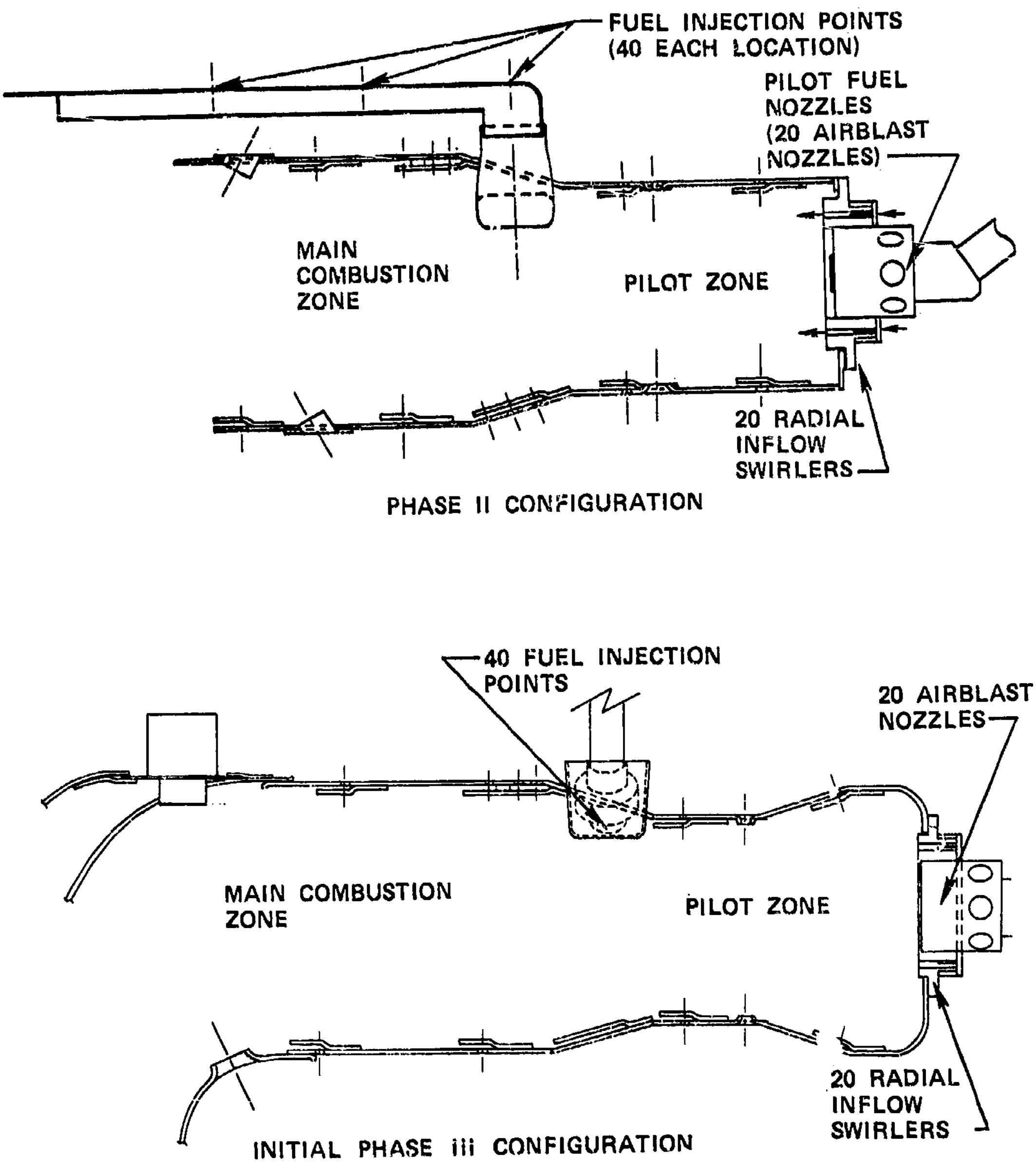

Figure 37. Concept 3 Combustor Configurations.

and two were performed with modified Phase II hardware. These latter tests were used to determine the NO_x reduction at the high-power points that could be anticipated with the new swirler design. The configuration of each of the tested designs is described in Table XVI, and the emissions levels attained are summarized in Figure 38. A brief description of the configurations and the test results is presented in the following paragraphs. The complete test results are included in Appendix B.

a. Modified Phase II Hardware, Rig Test No. 1 - To obtain preliminary test information on the Phase III design, a brief series of tests was planned to evaluate the effects of air added through the dome of the combustor at high-power operation. Phase II, Concept 2 hardware was used for these tests, and the intent of the modifications was to approximate progressively increased-airflow dome swirlers.

The first of these tests was run on the configuration shown in Figure 39. The combustion system was identical to the Optimization Test No. 1 configuration, with the addition of 3.1 mm wide slots in the form of arcs in the dome of the combustor surrounding the swirlers. This additional area in the dome was equivalent to the area added to the outer swirlers of the Phase III, Concept 2 design. The purpose of the extra area was to produce a leaner primary zone at the high-power settings, thereby resulting in a lower NO_x level.

The combustion system was tested at climbout and takeoff with the valves in the 90-degree (full-open) position. No variable-geometry linkage was installed, and the Phase II airblast nozzles were operated without assist air. The results of the takeoff test are shown below, along with Phase II Optimization Test No. 1 data for comparison:

	Takeoff Emissions Indexes			
	HC g/kg fuel	CO g/kg fuel	NO_x g/kg fuel	CO_2 %
Mod of Opt. No. 1	0.47	9.94	7.66	3.10
Opt. Test No. 1 (Phase II)	0.50	2.14	6.78	3.36

The data indicated that HC remained essentially unchanged, but that CO increased four times over the Optimization Test No. 1 results. CO_2 was down 8 percent. Even though NO_x showed an increase of 12 percent, this is somewhat misleading. A comparison of the measured NO_x levels shows 81.8 ppm for the modified combustor, and 78.0 ppm for Optimization Test No. 1 -- a 4-percent increase. The high NO_x EI results, in part, from the decreased CO_2 and the increased CO EI, which has a significant effect on the

TABLE XVI. CONCEPT 2 RIG TEST CONFIGURATIONS.

Rig Test Number	Modification (Compared to Phase II Refinement Test No. 1)
1.	New piloted airblast fuel nozzle with 0.7 flow-number pilots (counterrotating swirlers) New swirler-valve assemblies with larger outer swirlers and piston ring seals on the valves
2.	Modified pilot nozzles with the flow number increased to 1.0
3.	Combustor swirlers sealed to dome
4.	Scoops added to valve housings
5.	Inner swirlers on airblast fuel nozzles blocked
6.	All of swirler air blocked on the airblast fuel nozzles.
7.	New piloted airblast nozzle design used with lower airflow swirlers (corotating) Inner swirlers of the combustor swirlers blocked.
8.	Combustor swirlers were resealed to dome (repaired damaged seals). Removed blockage of combustor inner swirlers.

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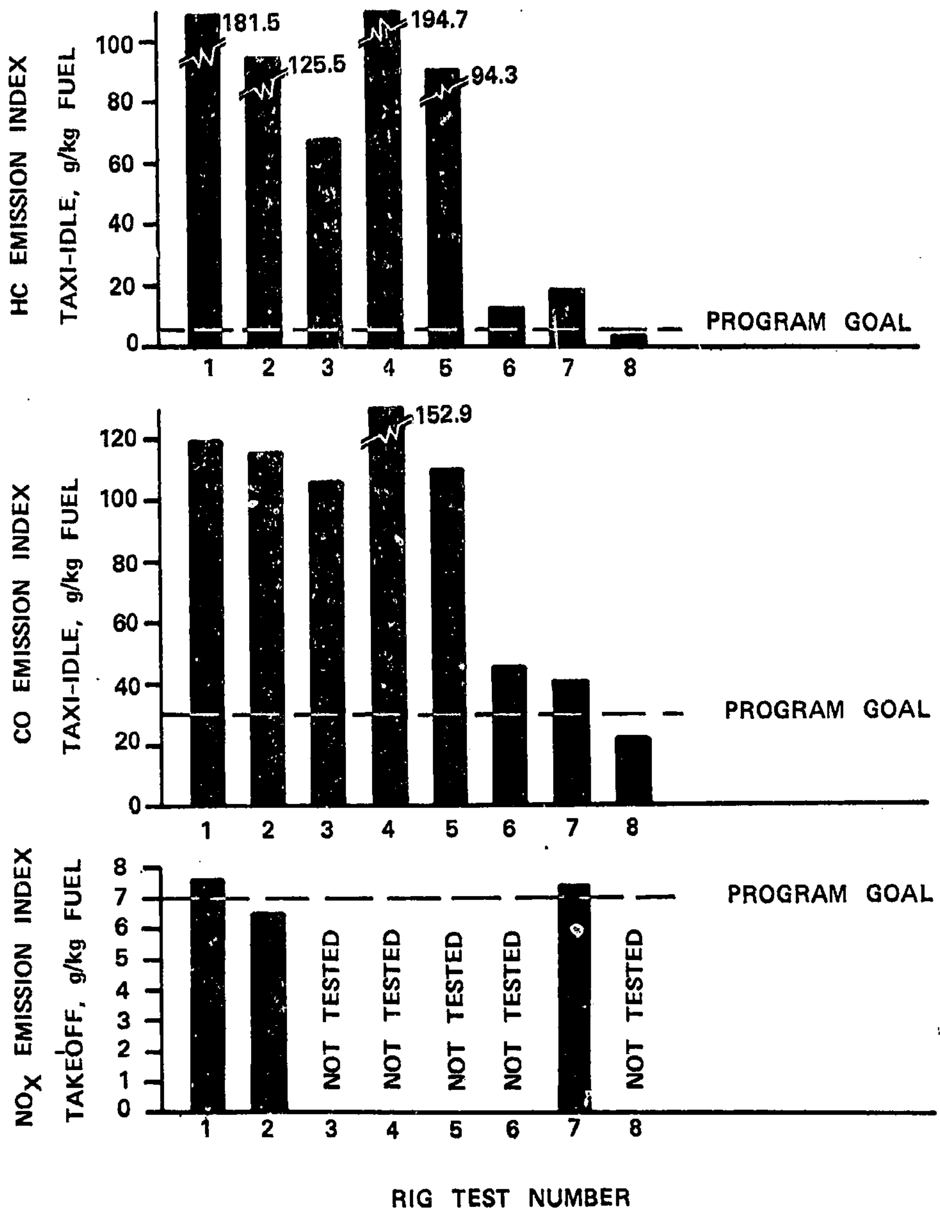


Figure 38. Summary of Emissions Results from Rig Tests.

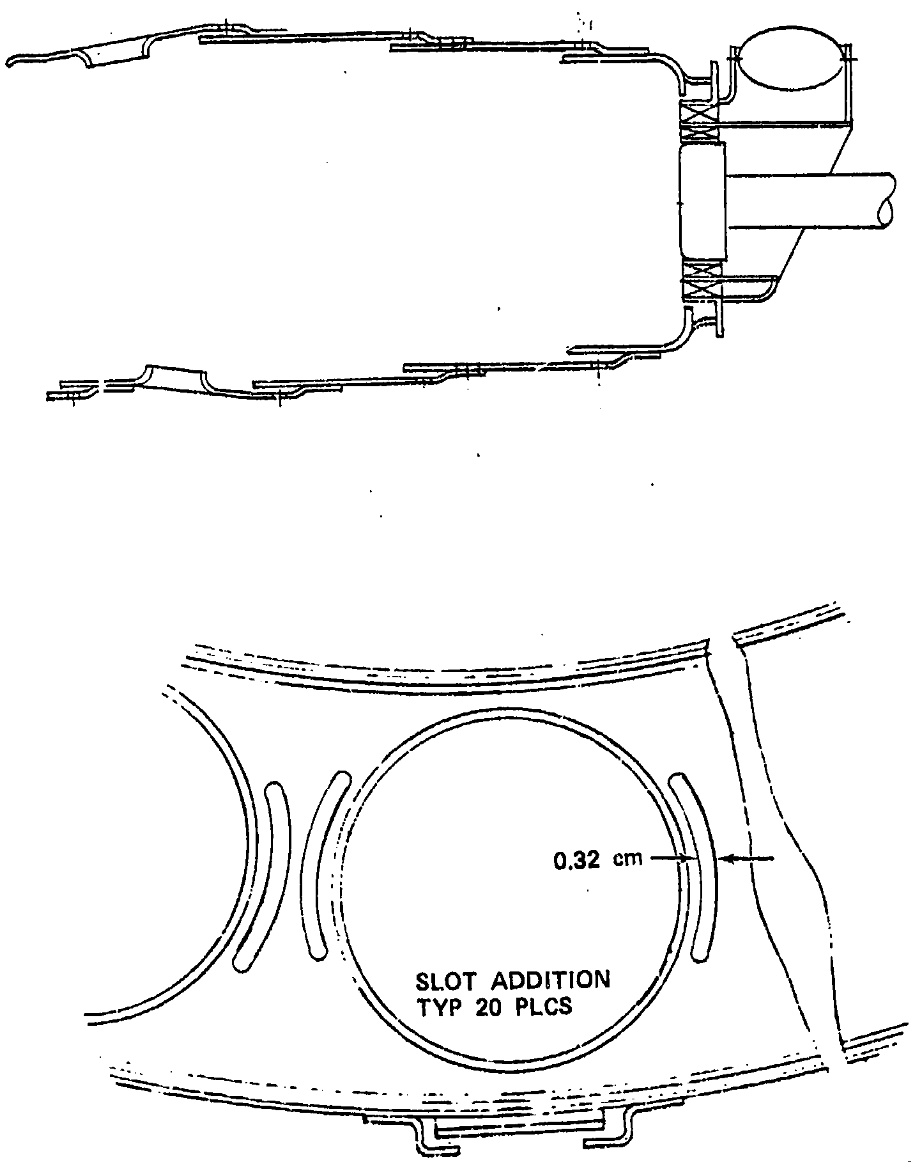


Figure 39. Combustor Schematic Showing Dome Slots Added to the Phase II, Concept 2 Optimization Test No. 1 Configuration.

NO_x EI calculation. All other combustor-performance parameters were satisfactory and in accord with the Optimization Test No. 1 results.

Teardown inspection revealed carbon buildup on the face of all 20 nozzles. The carbon was uniform in thickness (approximately 1.3 to 1.5 mm), and covered nearly all of the exposed nozzle surfaces. The remainder of the combustor was clean with no carbon deposits. The Optimization Test No. 1 system had no carbon buildup on the nozzles when run at the same conditions.

The airflow through the newly added slots apparently disrupted the reaction zone, causing a portion of the fuel-air mixture to wash against the fuel nozzle faces thereby producing the carbon buildup. This disruption also decreased the residence time of at least a portion of the reacting gases, which resulted in a four times increase in CO and a decrease in CO_2. The decrease in residence time was not of sufficient magnitude to cause a reduction in NO_x, and apparently the air injected through the slots did not effectively lower the reaction-zone equivalence ratio, as this would also have produced a NO_x reduction.

b. <u>Modified Phase II Hardware Rig Test No. 2</u> - The second design modification involved returning the combustor to the original Optimization Test No. 1 configuration by tack welding shimstock patches over the dome slots that were added for the first modification. Every other dilution hole was covered with a shimstock patch. This produced a calculated primary-zone equivalence ratio (ϕ_{pz}) equal to that of the first modification, but with primary-zone aerodynamics very similar to that of the Optimization Test No. 1 combustor. This ϕ_{pz} was also equal to the calculated ϕ_{pz} for the Phase III combustor. A schematic of the combustor is shown in Figure 40.

The combustion system was evaluated at climbout and takeoff with the valves in the 90-degree (full open) position. No variable-geometry linkage was installed, and the Phase II airblast nozzles were operated without air assist. The results of the takeoff test are presented below, along with data from the first modification test and the Phase II Optimization Test No. 1 configuration for comparison:

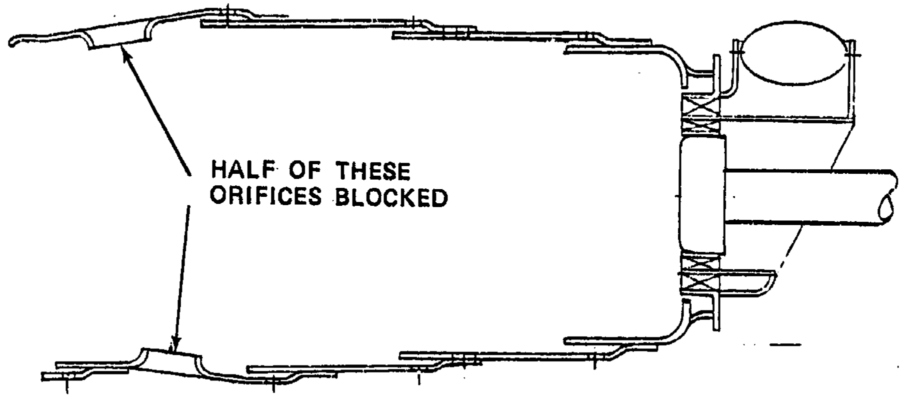


Figure 40. Schematic of Part 3551401-8 Combustor (Used in Rig Test).

	Takeoff Emissions Indexes		
	HC g/kg fuel	CO g/kg fuel	NO_x g/kg fuel
Mod 2 of Opt. No. 1	0.13	4.89	6.29
Mod 1 of Opt. No. 1	0.47	9.94	7.66
Opt. Test No. 1 Phase II)	0.50	2.14	6.78

The second modification produced a 7-percent reduction in takeoff NO_x while the CO level approximately doubled compared to Phase II data. However, the combustion efficiency from emissions of the second modification was 99.9 percent.

The data from this test were input into the EPAP program, using the taxi-idle and approach data from the Phase II engine test on the Optimization Test No. 1 combustion system with pressure atomizing fuel injectors. The NO_x EPAP was calculated by using a pressure-correction exponent of 0.5. The test values (compared with the program goals) are shown below:

	EPAP (lb/1000 lb thrust-hr/cycle)		
	HC	CO	NO_x
Mod 2 of Opt Test No. 1	0.95	6.35	3.86
Program Goals	1.60	9.40	3.70

This configuration met the HC and CO goals with considerable margin, and was close to meeting the NO_x goal.

c. Concept 2 - Phase III Hardware Rig Test No. 1 - The first combustion test on Phase III hardware consisted of running all EPA power-setting points and an altitude-cruise point. Parametric testing was limited to evaluating the effect of valve position on approach emissions; and the effect of fuel-flow split between the pilot and airblast secondary fuel nozzles on emissions at taxi-idle, approach, and takeoff. The combustion system is shown in Figure 41.

Upon completion of this testing, a rig-assembly problem was discovered and several fuel nozzles were found to produce either low-flow rates or distorted spray patterns. The nozzles were cleaned, the assembly problem corrected and the test was repeated.

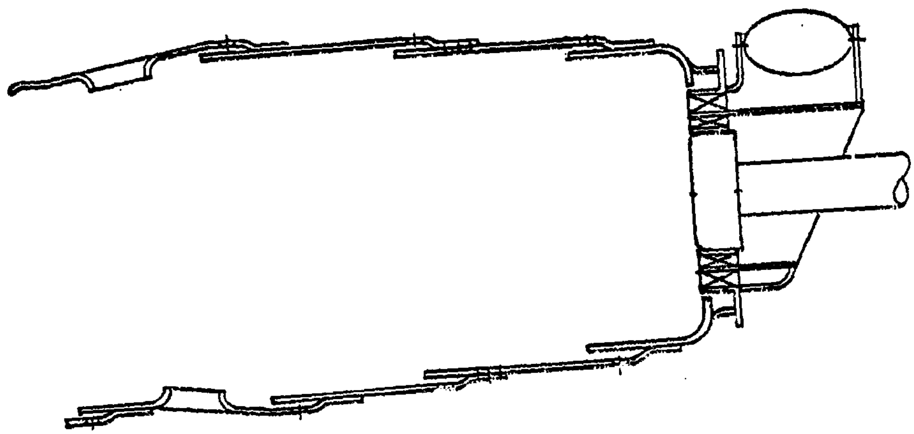


Figure 41. Concept 2, Phase III Hardware Rig Test No. 1 Combustor Configuration.

During the subsequent testing, purge cooling air was used to reduce the possibility of further fuel coking. With no fuel flowing, high-pressure (purge) air at ambient temperature was blown through the fuel manifold to maintain low-metal temperatures prior to ignition. When fuel to the pilots was to be discontinued, purge air was initiated prior to fuel cut off. In addition, pilot fuel flow was maintained at or above 45.4 kg/hr to ensure adequate fuel pressure to supply each nozzle and produce low-fuel residence time in the nozzles.

The emissions indexes (EI) are shown below, along with the program goals:

	Taxi-Idle EI		Takeoff EI
	HC g/kg fuel	CO g/kg fuel	NO_x g/kg fuel
Phase III Rig Test No. 1	181.5	119.8	7.49
Program Goals	6.0	30.0	7.0

Following the test, many of the nozzles were again found to be plugged (one of the secondary airblast nozzles had very low flow, which resulted in the poor emissions values at the high-power settings).

To prevent further nozzle plugging problems, it was decided to modify the pilot nozzle design. It was believed that the pilot fuel-flow problems stemmed from small metering slots in the fuel distributor (on the order of 0.1 mm). Specific modifications included increasing the pilot flow number from 0.7 to 1.0, and decreasing the number of metering slots from three to two. This produced metering slots with a square cross section, with a minimum dimension on the order of 0.3 mm.

d. Phase III Hardware Rig Test No. 2 - Prior to this test, Delavan modified the nozzles by increasing the flow number of the pilots to 1.0 and changing the pilot nozzle to a simplex, pressure atomizer assembly that screwed into the nozzle body. The simplex nozzle, which was similar to the pilot nozzle used in Phase II, used a less efficient fuel-metering distributor than the original design, thereby requiring an increase in the size of the fuel-metering slots. This increase, together with the required increase to accommodate the larger flow number, resulted in nozzle hardware with a greatly reduced tendency for carbon fouling.

A rig test was performed using the modified fuel nozzles and the same combustor configuration that was used in Rig Test No. 1.

Eleven test points were evaluated, including three at the taxi-idle inlet conditions with the valves shut and operating on pilots fuel nozzles only.

At the taxi-idle point there was only a slight improvement in HC from the previous test with the original pilot-nozzle design, with CO essentially unchanged. The taxi-idle point was repeated at the end of the high-power testing to determine if there was a variation with "hot" hardware. The data repeated almost exactly. Finally, a test was run at the taxi-idle inlet conditions with a 22.7 kg/hr increase in fuel flow (28-percent increase) to determine the effect of fuel/air ratio on combustion efficiency. The combustion efficiency was still less than 94 percent. The HC, CO, and combustion efficiency for these taxi-idle points, together with the results of the previous test with the unmodified nozzles and the program goals, are shown below:

	Taxi-Idle Emissions Indexes		
	HC g/kg fuel	CO g/kg fuel	Combustion Eff, %
Rig Test No. 1	181.5	119.8	81.5
Rig Test No. 2	125.5	116.8	86.2
Rig Test No. 2, rerun	122.8	125.2	86.3
Rig Test No. 2, 22.7 kg/hr increased fuel flow	46.0	88.8	93.9
Program Goals	6.0	30.0	99.0+

At the simulated takeoff conditions, three fuel-flow splits (primary-secondary) were evaluated with pilot flows of 48.1, 71.7 and 95.7 out of a total of approximately 213.2 kg/hr. The fuel-flow splits had little or no effect on emissions levels, which were similar to those measured on Rig Test No. 1 while running on secondaries only. These results are shown below, along with the program goals:

	Takeoff Emissions Indexes		
	HC g/kg fuel	CO g/kg fuel	NO_x g/kg fuel
Rig Test No. 1, Secondaries only	0.64	7.40	6.46
Rig Test No. 2, 48.1 kg/hr primary	0.07	9.78	6.58
Rig Test No. 2, 71.7 kg/hr primary	0.01	10.18	6.51
Rig Test No. 2, 95.7 kg/hr primary	0.03	10.07	6.51
Program Goal	--	--	7.00

e. Phase III Hardware Rig Test No. 3 - Based on experience from Phase II where small amounts of air leakage in the vicinity of the swirlers and fuel nozzles produced high HC and CO levels at the taxi-idle conditions, it was decided to seal the variable-geometry swirler-valve assemblies to the combustor dome. A high-temperature-resistant (811 K) silicon base material with some flexibility was used as a sealant, and the sealed area was covered with shim stock to protect it from direct flame contact and radiation (see Figure 42). This configuration was then tested on pilot nozzles only at the taxi-idle conditions with the valves shut. The emissions results of this test, together with the results from the previous test and the program goals are shown below:

	Taxi-Idle Emissions Indexes		
	HC g/kg fuel	CO g/kg fuel	Combustion Eff, %
1. Rig Test No. 3, sealed swirlers	68.4	107.5	91.5
2. Rig Test No. 2	125.5	116.8	86.2
3. Program goals	6.0	30.0	99.0+

The test data revealed an approximate 50-percent reduction in HC from the last test, while CO remained essentially unchanged.

As a result of the low combustion efficiency at the taxi-idle conditions (with hardware that was designed to be similar to the

Figure 42. Shim Stock Covering Air Leakage Path Around Swirler.

Phase II hardware that produced low taxi-idle emissions) a direct comparison was made between the two sets of hardware. Both combustors were dimensionally inspected in detail and the effective flow area of each row of orifices and cooling holes was determined. The fuel nozzles were compared to the pressure atomizers used at the end of Phase II with respect to droplet size and cone angle, both with and without shroud and swirler airflow. Also, the possibility of increased valve body housing size causing increased blockage and distorted flow to the small inner swirler was evaluated.

Dimensionally, both combustors were within print tolerances. The location of the rows of orifices were essentially identical. Determination of the effective area of these rows of orifices revealed that with the exception of the inner cooling band at the discharge of the combustor, the effective areas were also essentially identical. The difference in area of the discharge inner cooling band is assumed to have no appreciable effect on emission production. The results of these flow tests are included in Appendix A.

The Phase III piloted-airblast nozzle swirler had 91 percent more open area than that of the Phase II pressure atomizer which was used in the Phase II engine test that demonstrated low-idle emissions. The fuel-spray pattern of the Phase III pilot nozzles was similar to that of the Phase II pressure nozzles, and both spray cones had a tendency to collapse as the nozzle swirler airflow was increased.

f. Phase III Hardware, Rig Test No. 4 - It was decided to determine whether the increased blockage of the swirler valve housings was causing the low combustion efficiencies of Test No. 3 by distorting the airflow to the combustor inner swirlers and fuel-nozzle swirlers. The valve housings were modified by adding a scoop to the downstream side of each assembly, thereby producing a larger capture area for the swirlers. In addition, two fuel nozzles were each instrumented with four static-pressure taps 90-degrees apart to measure the distortion of air flowing into the swirlers. The two instrumented nozzles were installed 90-degrees apart to determine circumferential variation in the swirler feed air. One of the two igniters was replaced with a probe to determine the static pressure inside the combustor. This was used to determine the static pressure loss across the swirlers for the purpose of calculating swirler airflow.

Two test points were run with this configuration: taxi-idle and approach. The taxi-idle emissions results are shown below, together with the results of the previous test without scoops and the program goals for comparison:

	Taxi-Idle Emissions Indexes	
	HC g/kg fuel	CO g/kg fuel
Rig Test No. 4 with scoops	194.7	152.9
Rig Test No. 3 without scoops	68.4	107.5
Program Goals	6.0	30.0

The static pressure on the instrumented fuel nozzles was almost identical, showing no distortion or circumferential variation. The static pressure loss across the swirlers was 4.6 percent, indicating adequate feed. The HC level was increased by 190 percent, and CO by 50 percent.

g. Phase III Hardware, Rig Test No. 5 - The significant increase in emissions levels in Rig Test No. 4, and the uniformity of the air feed to the dome, indicated that the reaction was too lean in the vicinity of the fuel-injection points and the next modification involved blocking the inner swirler of the fuel nozzles. This produced a nozzle-swirler effective area closer to that of the pressure atomizer used in Phase II. The scoops were maintained to ensure even air feed, and the instrumented fuel nozzles were also used.

This configuration was tested at three taxi-idle points; two with decreased airflows, and at climbout.

The taxi-idle emissions values are shown below:

	Taxi-Idle Emissions Indexes	
	HC g/kg fuel	CO g/kg fuel
Rig Test No. 5	94.3	114.9
Rig Test No. 5 (18.7 percent lower airflow)	24.4	49.4
Rig Test No. 5 (29.2 percent lower airflow)	7.3	27.1
Rig Test No. 4	194.7	152.9
Program Goals	6.0	30.0

Reducing the airflow through the nozzle swirlers brought the idle emissions close to the values attained before the scoops were added. However, the reduced airflow test data indicated that reductions in emissions could be achieved by further enriching of the reaction zone.

At climbout, the results were as follows:

	Climbout Emissions Indexes		
	HC g/kg fuel	CO g/kg fuel	NO_x g/kg fuel
Rig Test No. 5	0.6	12.7	5.8
Rig Test No. 3	0.1	13.1	6.1

h. Phase III Hardware, Rig Test No. 6 - As a result of the improved taxi-idle emissions levels demonstrated with partially blocked fuel-nozzle swirlers during the previous test, the next test configuration involved running with all of the fuel-nozzle swirlers blocked. This configuration was not considered a viable engine system since no airflow would be available to atomize the fuel of the airblast secondaries. However, the purpose of the test was to determine if further reductions in taxi-idle emissions were attainable with an increased reaction-zone fuel/air ratio.

The combustion system was tested at five taxi-idle points. Two of the points had increased fuel flow to simulate a richer reaction zone while maintaining a constant reference velocity. Two other points were run with the taxi-idle fuel flow and reduced airflow rates to produce a richer reaction zone with a decreased reference velocity. The actual taxi-idle emissions are presented below, together with the results of the previous test and the program goals for comparison:

	Taxi-Idle Emissions Indexes	
	HC g/kg fuel	CO g/kg fuel
Rig Test No. 6	11.8	44.5
Rig Test No. 5	94.3	114.9
Program Goals	6.0	30.0

A significant reduction in both HC and CO was demonstrated with this configuration. Figure 43 illustrates the trends of HC and CO as a function of fuel/air ratio, and shows that further reductions in these pollutants are possible by enriching the reaction zone. The figure also shows that decreasing reference velocity had no significant effect on pollutant formation.

Inspection of the combustion system after disassembly revealed that the airblast swirler passages of all 20 fuel nozzles were plugged with carbon. Attempts to clean the nozzles were unsuccessful. The nozzles were returned to Delavan where a new tip design was installed. This tip had corotating airblast swirlers as opposed to the counterrotating design used in the previous configuration. Airflow measurements on the nozzles indicated an effective area reduction of 16 percent compared to the previous design. The 1.0 flow number pressure atomizers were retained as pilot injectors.

i. Phase III Hardware, Rig Test No. 7 - The next modification involved blocking the combustor inner swirlers. The new fuel nozzles were used unmodified. This resulted in a 26-percent reduction in the effective area over the previous configuration, thus producing a richer reaction zone. Additionally, this configuration allowed operation at the high-power points on the airblast portion of the nozzles. The possible drawback to this design was that during Phase II (while using the smaller airflow fuel nozzles) low taxi-idle emission levels were unattainable without the use of combustor inner swirlers.

The combustor was tested at the four LTO power-setting points and one additional taxi point with elevated fuel flow. At the taxi and approach points, the valves were closed. At climbout and takeoff the valves were full open. The taxi-idle emissions levels are shown below, together with the results of the previous configuration and the program goals for comparison:

	Taxi-Idle EI	
	HC g/kg fuel	CO g/kg fuel
Rig Test No. 7	18.2	40.5
Rig Test No. 6	11.8	44.5
Program Goals	6.0	30.0

The configuration showed a slight improvement in CO but an increase in HC. This HC increase is thought to have occurred because of the quenching effect of the nozzle airflow, which was blocked in the previous configuration.

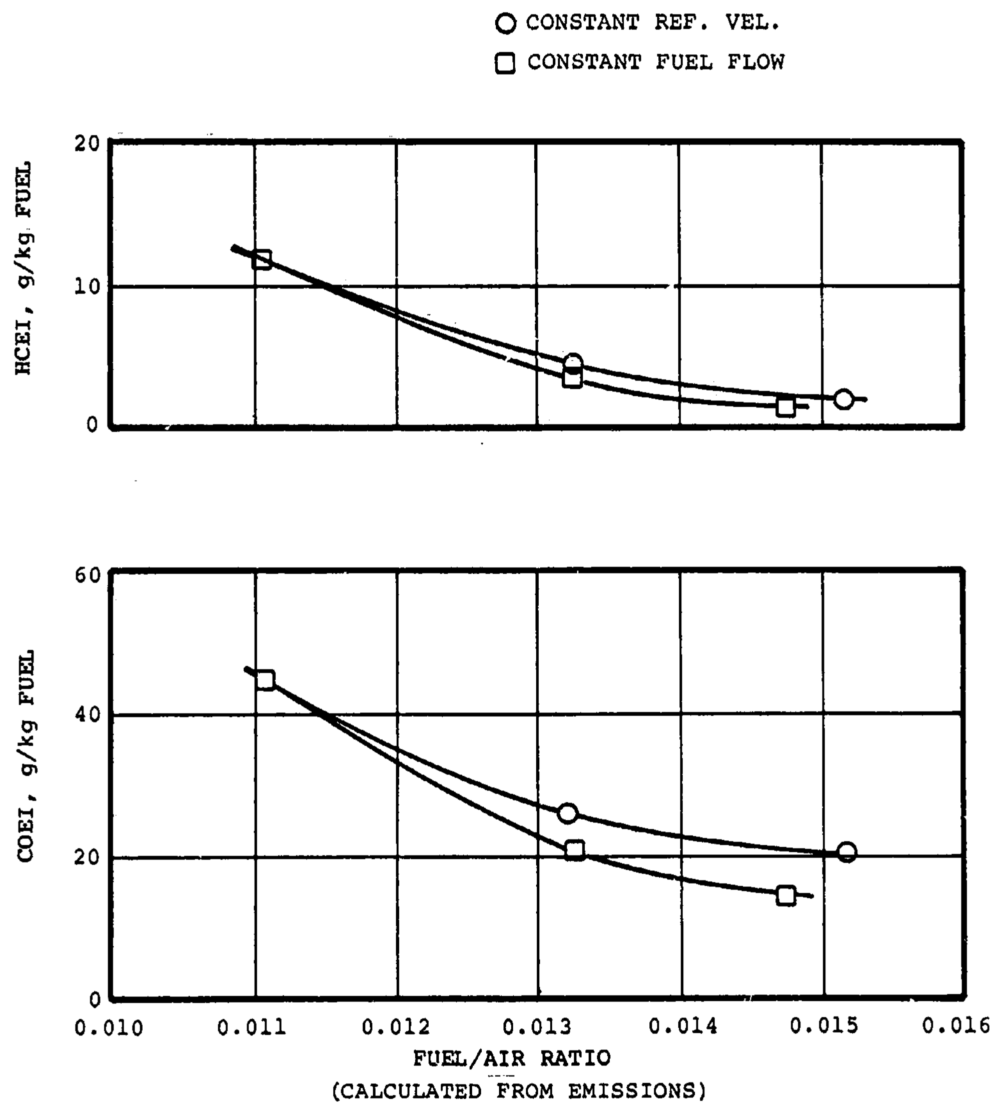


Figure 43. HC and CO Emissions for Concept 2 Rig Test No. 6.

At the climbout and takeoff points, the NO_x levels were slightly above those of the previous configuration tested at the high-power settings, as shown below:

	NO_x EI g/kg fuel	
	Climbout	Takeoff
Rig Test No. 7	6.7	7.4
Rig Test No. 3	6.1	6.6
Program Goal	---	7.0

The takeoff NO_x level was slightly above the program goal, and 12 percent above the previous configuration. This increase is attributed to the decreased reaction-zone airflow caused by the blocked inner combustion swirlers.

Although the individual emissions indexes for this configuration exceeded the program goals, when engine-to-rig correlations (determined during Phase II on the Concept 2 Optimization No. 1 configuration) were applied, the configuration met, or was close to meeting, the program goals. Therefore, it was concluded that the initial engine test would be performed with this configuration to determine if more rig development was required.

j. Phase III Hardware, Rig Test No. 8 - As the result of increasing HC and CO values at the low-power settings during engine testing, the Concept 2 combustor was removed and modified. The swirler-dome seal had deteriorated due to extensive rig and engine testing. The modification consisted of resealing the swirlers to the combustor dome and the sealing of the leak path between the fuel nozzles and inner swirlers. The sealing was accomplished using a high-temperature silicone rubber compound. The internal seals (between the swirlers and combustor) used shim-stock patches to protect them from thermal radiation and erosion due to the velocity of the combustion gases. Additionally, the washers used to block the inner swirler airflow were removed.

The combustor was installed in the combustion rig and tested at taxi-idle only (to extend the seal life). The variable-geometry valves were set to the closed position, and the test was made on pilot fuel nozzles only. The emissions values are summarized below:

	Taxi-Idle Emissions Indexes	
	HC g/kg fuel	CO g/kg fuel
1. Rig Test No. 8	3.3	21.9
2. Rig Test No. 7	18.2	40.5
3. Program Goals	6.0	30.0

The data shows that this configuration met the taxi-idle emission goals for both HC and CO.

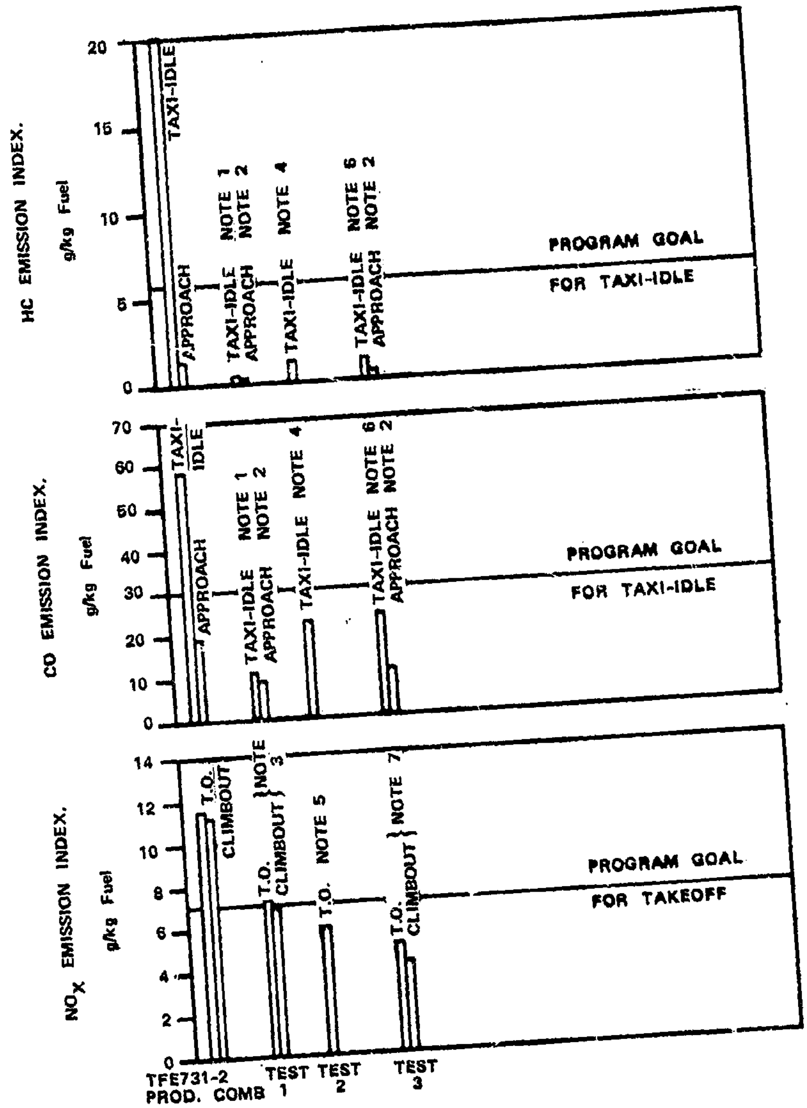
2. Concept 3 - Configurations and Emissions Results - The Phase III modifications to the Phase II configuration are listed in Table XVII along with the two modifications that were made to the initial configuration. The emissions results obtained in each of the three tests are given in Figure 44. Testing was conducted to select the pilot zone that gave the optimum degree of pilot-zone mixedness. The optimum configuration sought would produce high efficiency at taxi-idle and a strong ignition source for the main combustion zone at high-power conditions. The objective of testing each modification was to obtain the optimum fuel-flow split between the pilot- and main-combustion zone at each of the three high-power conditions. The optimum fuel split produced pilot-zone exit temperatures high enough to ignite the main fuel and produce high efficiencies, but sufficiently low to minimize the pilot-zone NO_x emissions.

a. Test No. 1 - A cross-sectional drawing of the baseline configuration is shown in Figure 45. The main fuel nozzles consisted of 40 equally-spaced, air-assisted pressure atomizers with flow numbers of 0.7. They were inserted into individual air tubes that fed 24 percent of the inlet airflow into the combustor at the axial mid-point. The pilot zone at the dome of the combustor was fueled by 20 air-assisted airblast nozzles inserted axially through the combustor endplate. The swirlers were of the radial-inflow type, and were the result of extensive testing in Phase II to select the swirler that produced the highest efficiency. The swirlers were sized to produce a pilot-zone equivalence ratio of 0.8 at taxi-idle.

The HC and CO values obtained at the taxi-idle condition are presented in Figure 46 as a function of air-assist pressure. Also given are the best results of Phase II. The HC and CO emissions goals were achieved with less (140 kPa) air-assist differential pressure than that required in Phase II. The improvement can be attributed to the larger pilot-zone volume.

TABLE XVII. CONCEPT 3 TEST CONFIGURATIONS.

Test No.	Modification (Comparison to Phase II Configuration)
1	Premixing eliminated; main fuel is injected by air-assisted pressure atomizers, inserted through individual air tubes, directly into the combustor. The dilution orifices were removed from the combustor liner and placed in the inner and outer transition liners to provide more residence time for the main zone. The primary zone volume was increased 13 percent to provide a stronger ignition source for the main zone combustor. The liner cooling airflow in the dilution zone was reduced.
2	Dilution orifices placed back in combustor liner.
3	Pilot nozzles changed from air assisted airblast to simplex pressure atomizers.



NOTES:

1. 414 KPA AIR ASSIST DIFFERENTIAL PRESSURE
2. 1% MAIN STAGE FUEL FLOW
3. 345 KPA AIR ASSIST DIFFERENTIAL PRESSURE
4. 138 KPA AIR ASSIST DIFFERENTIAL PRESSURE
5. NO AIR ASSIST
6. NO AIR ASSIST
7. 345 KPA AIR ASSIST

Figure 44. Summary of Emission Test Results, Concept 3.

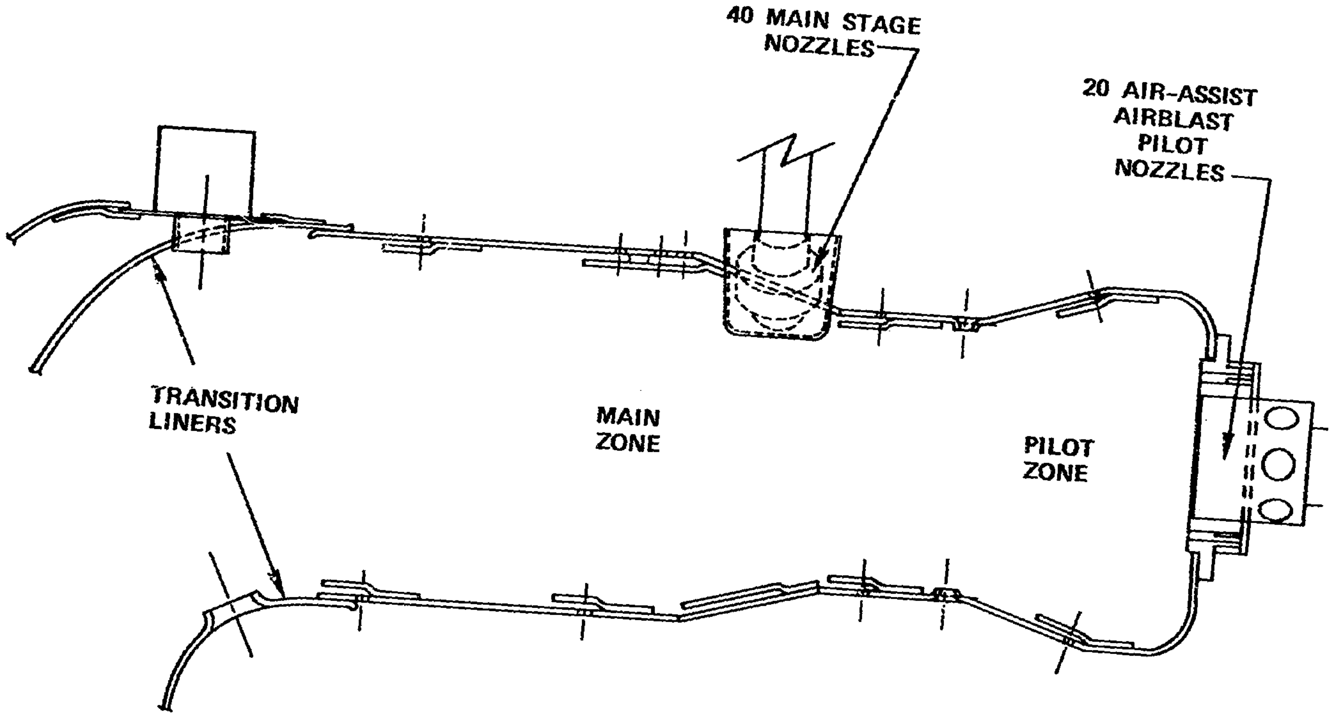


Figure 45. Concept 3, Test 1 Configuration.

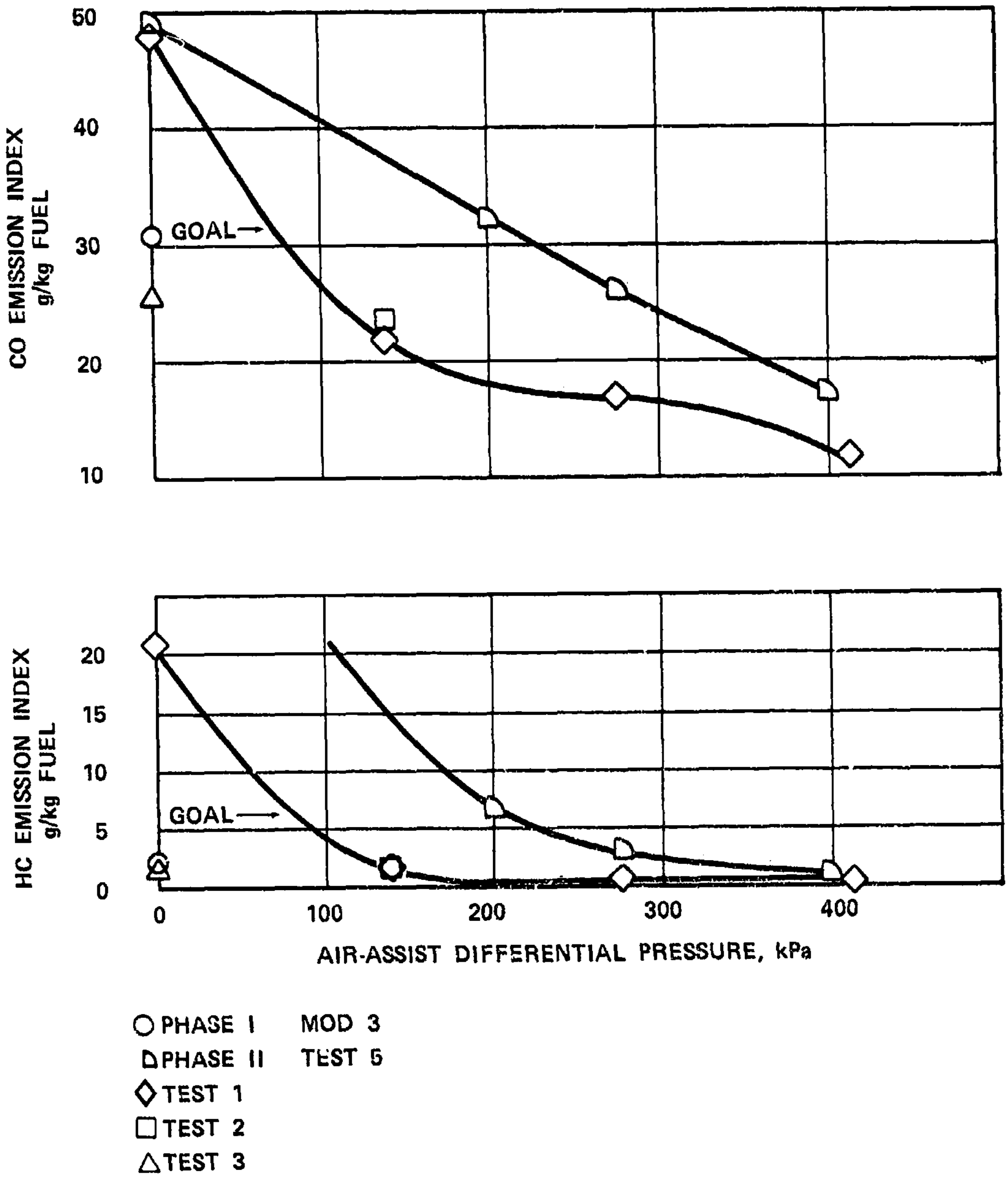


Figure 46. Effect of Air Assist on CO and HC Emissions at Taxi-Idle.

The combustion efficiency at the approach condition was the highest of any configuration tested in Phases II or III. The efficiency as a function of pilot-main fuel-flow split is plotted in Figure 47. The improvement in efficiency was probably due to a 36-percent increase in main-zone combustion residence time (due to moving the dilution orifices downstream), and also to the larger pilot-zone volume that would have created a better ignition source for the main stage resulting in a higher efficiency.

The amount of main-stage fuel flow was varied from 60 to 80 percent of the total fuel flow at the takeoff condition to evaluate the effect of the pilot-main fuel-flow split. NO_x emission values and combustion efficiency at takeoff are plotted versus fuel flow split in Figure 48. The efficiency met the requirements; however, the NO_x levels exceeded the goals. Furthermore, the NO_x emissions increased with increasing main-stage fuel flow, indicating that the principal source of NO_x was the main stage. The majority of the NO_x emissions was formed in the pilot zone in Phase II. The effect of air assist on the main nozzles was to lower NO_x emissions by 11 percent at a pressure of 345 kPa.

Post-test teardown revealed erosion of the main nozzle tips. Nozzle tips with a higher flow number (1.0) were used as replacements.

The high NO_x levels of the first test indicated inadequate mixing was occurring in the main stage; the average droplet size produced by the main nozzles was not sufficiently small to produce a well-mixed, lean reaction zone.

b. Test No. 2 - A cross-section view of the second test configuration is given in Figure 49. The dilution orifices were removed from the transition liners and placed in the combustor liner at the same location as in Phase II. This was done to decrease the NO_x levels produced by the main stage by decreasing the reaction time. The pilot zone remained unchanged and produced identical results at taxi-idle as Test 1 (as shown in Figure 46).

The reduction in residence time produced NO_x levels below the goal at takeoff (as shown in Figure 48). The trend, observed in Test 1, of increased NO_x with increased main-stage fuel flow was reversed, and therefore the main stage was no longer the principal source of NO_x emissions. The efficiency at the takeoff condition was unacceptable, and no further testing was done.

The low efficiency at the takeoff condition indicated that the pilot zone was not igniting the main fuel sufficiently to allow complete combustion to take place in the available residence time.

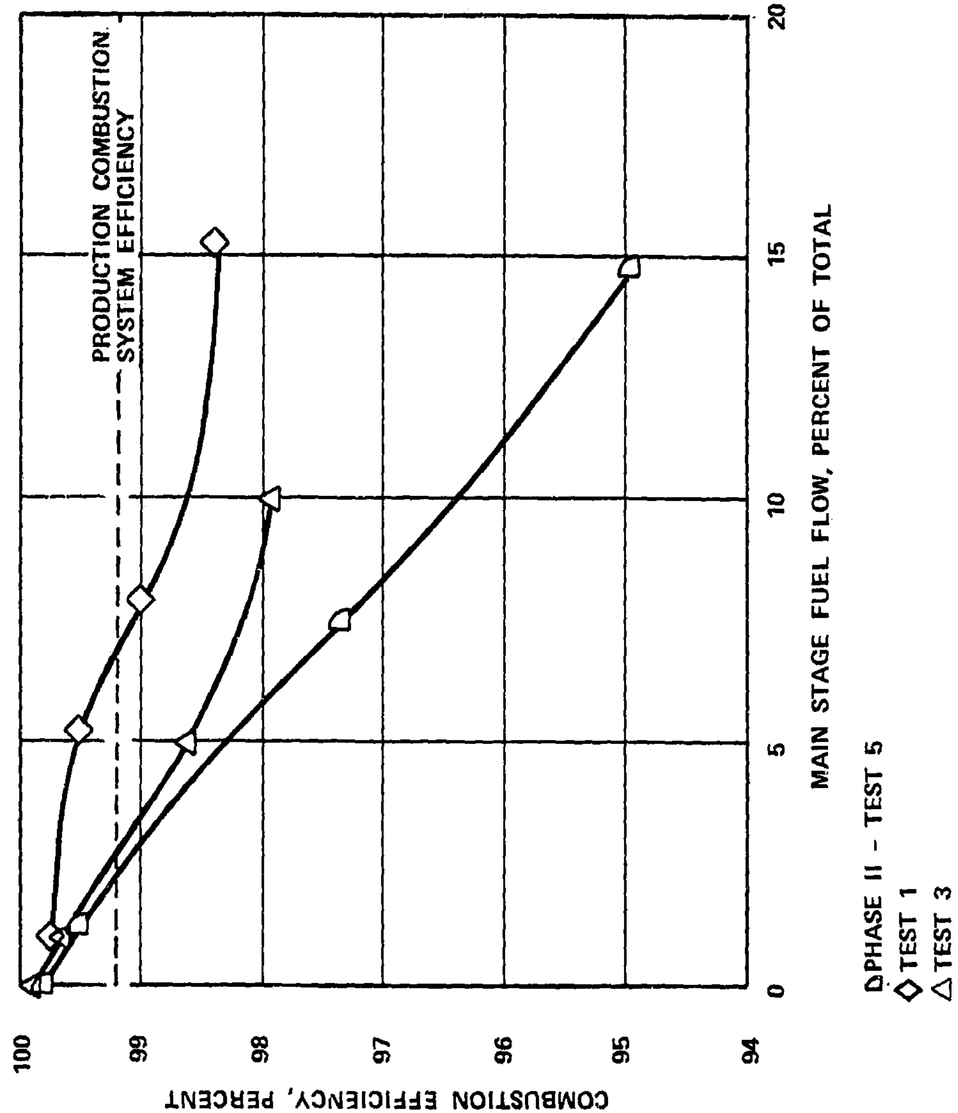


Figure 47. Effect of Fuel Flow Split on Combustion Efficiency at Approach.

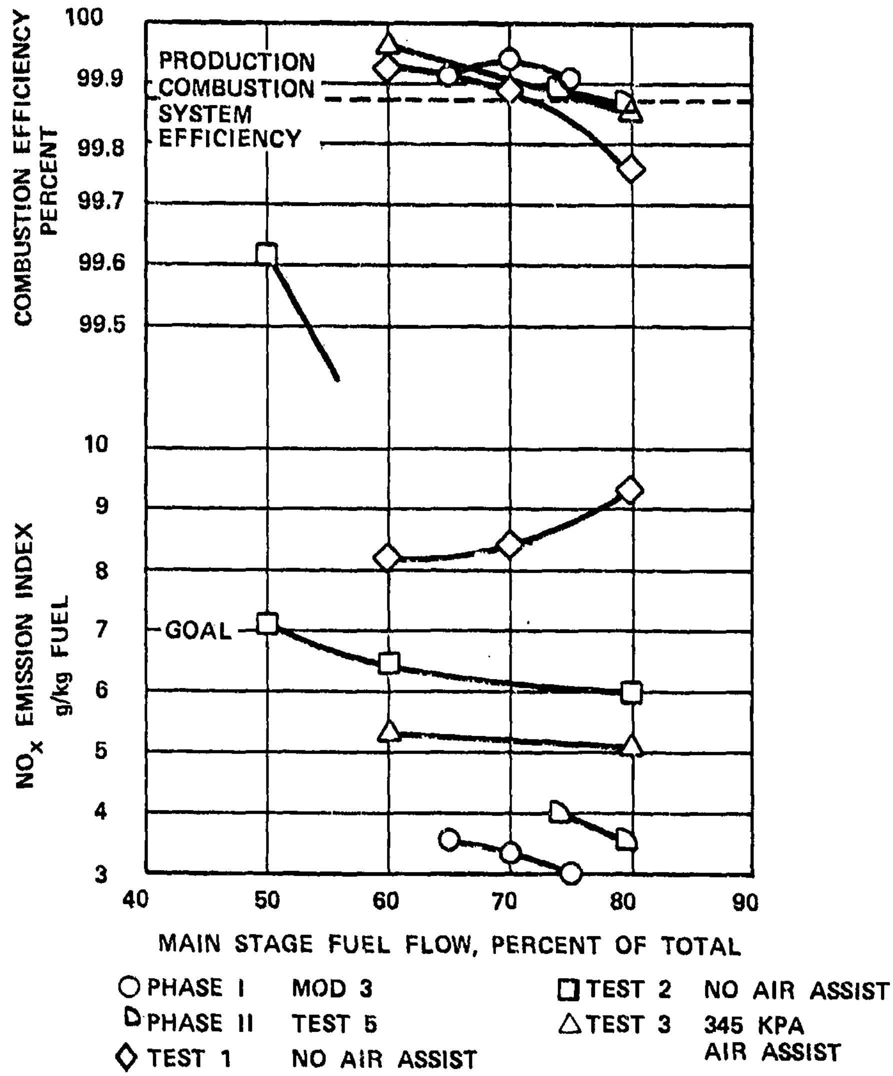


Figure 48. Effect of Fuel Flow Split on Combustion Efficiency and NO_x Emissions at Takeoff.

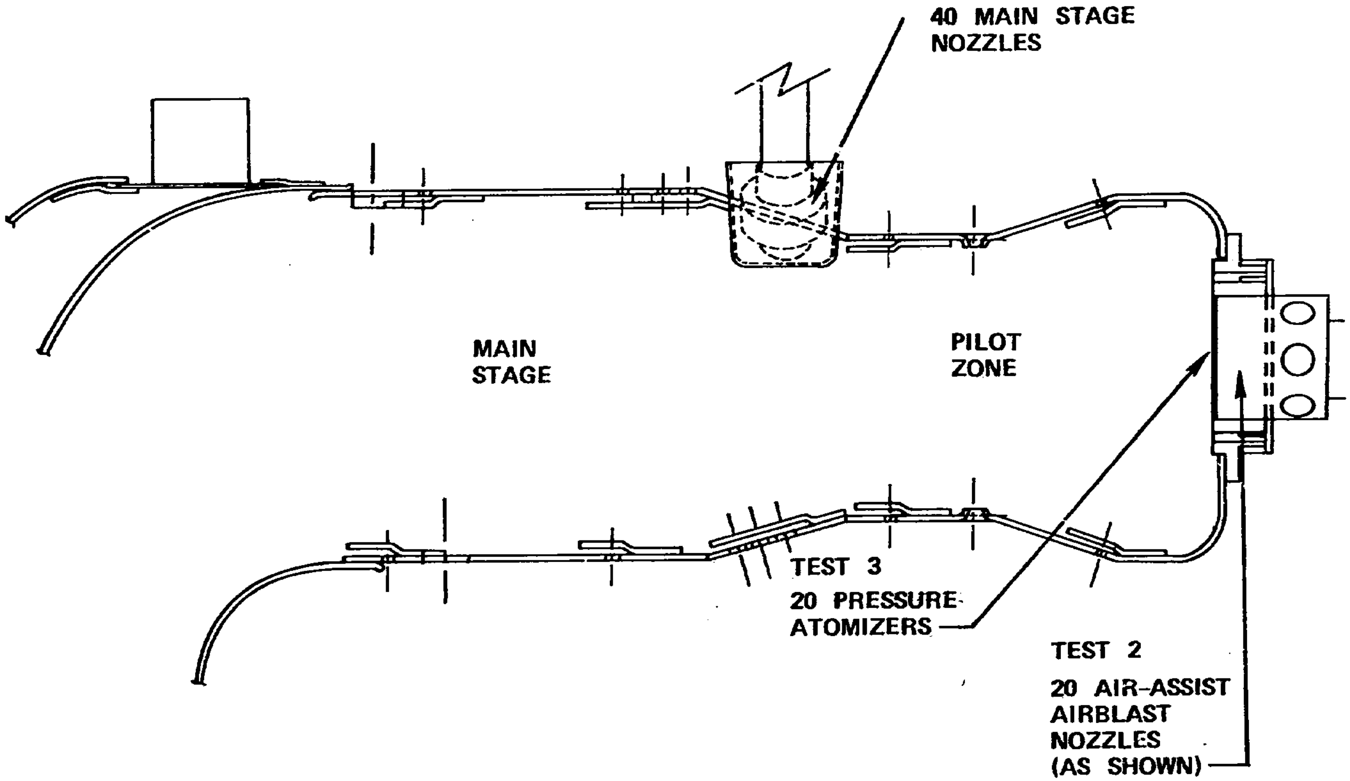


Figure 49. Concept 3, Tests 2 and 3 Configurations.

c. Test No. 3 - The degree of pilot-zone "mixedness" was decreased for the final test in order to increase the strength of the ignition source for the main zone. To accomplish this, the pilot nozzles were changed from air-assisted airblast to simplex pressure atomizers with a flow number of 0.7. The combustor is shown in Figure 49.

The HC and CO emissions at taxi-idle were the lowest achieved with any configuration without the use of air assist.

The NO_x levels without air assist were unchanged from those of Test 2; however, with 345 kPa air assist the NO_x decreased 15 percent. The NO_x values with air assist were well below the goals, and were less than half of the levels produced by the production system. However, the values were higher than those achieved in Phases I or II. The combustion efficiency was comparable to the best achieved in Phase II because of the increased strength of the main-zone ignition source (see Figure 48). Similar results were obtained at the climbout condition.

The SAE smoke number was measured to be 9.5 at the simulated climbout condition at one-third the full engine pressure and with 80-percent main-stage fuel flow. No reliable correction is known by the authors for the effect of pressure on smoke produced by a lean combustor, but the smoke number represents a significant reduction from the baseline combustor value of 16 at rig conditions.

In order to operate the rig at the same pressure as the engine at the approach condition, the pilot-nozzle tips were changed to a higher (1.0) flow number. Thus, a dual-orifice atomizer would be required for engine testing of this configuration. The combustion efficiency measured at the approach condition was not as high as in the first test because of the reduced residence time, but the efficiencies were higher than Phase II data (see Figure 47). The smoke number was measured to be 14 at the approach condition, with 10-percent main-stage fuel flow. The baseline combustor smoke number was measured to be 38 at approach.

3. Combustor Rig Performance - In addition to the gaseous emission measurements made on the various combustor configurations, performance data were also taken. Pressure loss and pattern-factor data were taken and recorded for all test points by the digital acquisition data system. These parameters are presented in Table XVIII for the taxi-idle and takeoff points. The values represent the pressure loss and pattern factor that correspond to the test point that produced the lowest emissions results.

TABLE XVIII. SUMMARY, PRESSURE LOSS AND PATTERN FACTOR.

	Taxi-Idle		Takeoff	
	Pressure Loss $\Delta P/P$, %	Temp Spread Factor	Pressure Loss $\Delta P/P$, %	Temp Spread Factor
Concept 2				
Phase II Hardware Test No. 1	----	----	4.9	0.09
Phase II Hardware Test No. 2	----	----	6.3	0.13
Rig Test No. 1	6.5	0.36	4.9	0.23
Rig Test No. 2	6.3	0.14	4.7	0.10
Rig Test No. 3	7.1	0.11	----	----
Rig Test No. 4	7.7	0.17	----	----
Rig Test No. 5	7.7	0.14	----	----
Rig Test No. 6	7.1	0.10	----	----
Rig Test No. 7	8.3	0.08	----	----
Rig Test No. 8	8.3	0.11	5.5	0.09
Rig Test No. 9	7.5	0.23	----	----
Concept 3				
Test No. 1	----	0.23	4.0	0.32
Test No. 2	4.85	0.18	6.15	0.18
Test No. 3	4.8	0.16	5.8	0.155

Liner-wall temperature tests were performed at the simulated takeoff condition on the configuration selected for the first engine test. Stability and ignition tests were also run on this configuration.

a. Pressure Loss - The present production combustion system has a pressure loss of 4.5 percent at the takeoff power setting, and the design criterion was to maintain this value as closely as possible for all configurations. The pressure loss on reverse-flow combustors is measured from the diffuser discharge (downstream of a set of deswirl vanes) to the stator inlet. For Concept 2, the takeoff pressure losses ranged from 4.9 to 5.5 percent for the various configurations. Rig Test No. 8, which was selected for the initial engine test, had a 5.5-percent value; and while this is higher than the goal, it was felt that the pressure loss could be reduced if engine tests had proved it necessary.

The Concept 3 configuration that produced the best results, Test 3, had a 5.8-percent pressure loss. The reason for the high pressure drop is unknown, since the Phase III combustor had the same open area as in Phase II where the pressure drop was measured to be 4.0 percent. However, the pressure loss could easily be reduced by increasing liner area with a minimal effect on emissions.

b. Exit Temperature Pattern Factor - The program goal for takeoff pattern factor is a value of 0.19 or less. Table XVIII indicates that the Concept 2 configuration selected for the initial engine test, Rig Test No. 8, had a takeoff pattern factor of 0.092, well below the program goal.

The initial configuration of Concept 3 exceeded the pattern factor goal, as can be seen in Table XVIII, because of the placement of the dilution orifices in the transition liners. The length available for the dilution jets to mix with the combustion gases was decreased 35 percent, and resulted in pattern factors greater than 0.3. When the dilution orifices were returned to the combustor liner, the pattern factors were within the goal.

c. Combustor Durability - Temperature-sensitive paint was used to determine the acceptability of the Concept 2 Rig Test No. 8 combustor for engine testing. The outer panels of the combustor, shown in Figure 50, reveal uniform liner temperatures, which were also observed on the inner panels. The majority of the liner was below 950 K, with two small areas on the inner panel adjacent to the primary orifices having temperatures of 1089 K. These levels were considered satisfactory for the initial engine test.

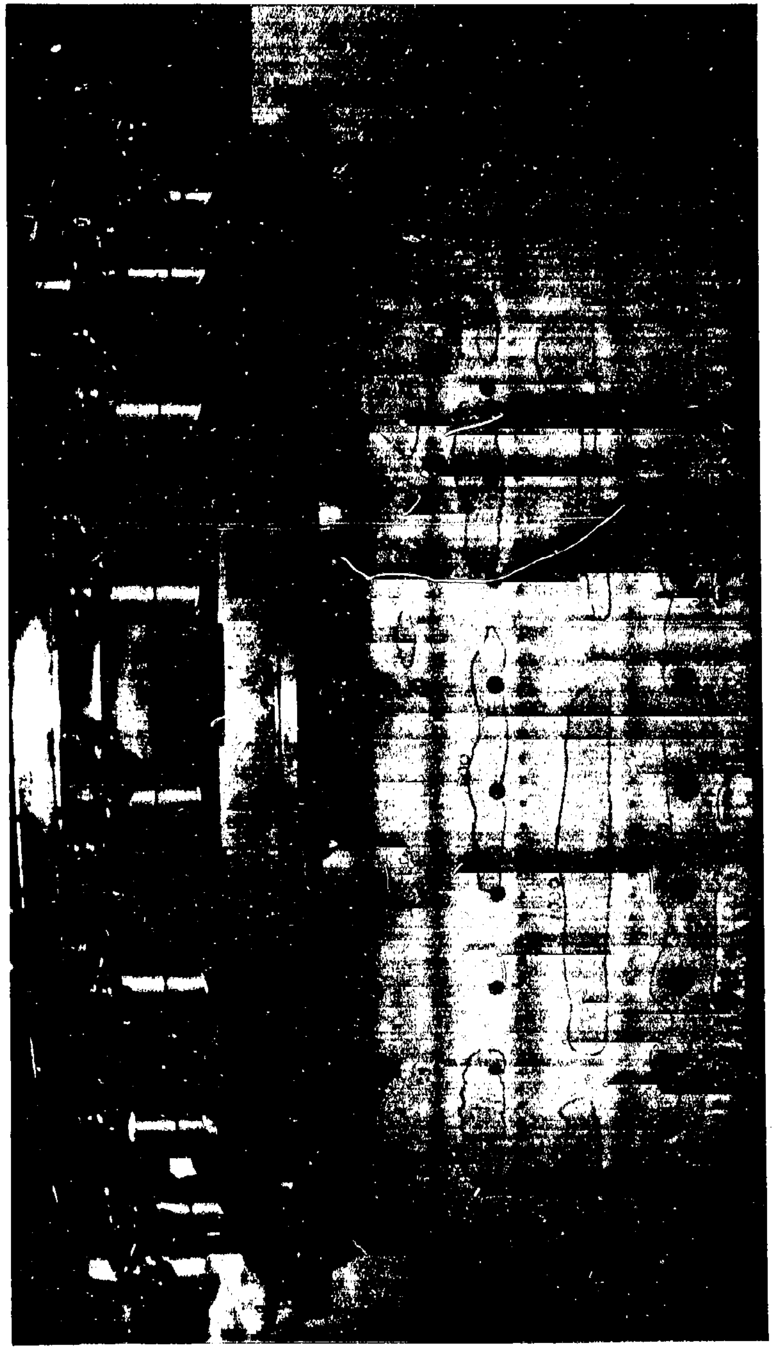


Figure 50. Temperature Distribution, Combustor Outer Panel.

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Hot regions as high as 1200 K were observed on the Concept 3 combustor in the primary zone, as shown in Figure 51. The hot regions occurred near the swirlers and primary orifices, and can be attributed to the increase in combustor channel height, since that is the only change in the primary zone from Phase II. The pilot-zone liner temperatures were much less in Phase II. The Phase III combustor would require further development to meet the combustor life goals, such as a smaller channel height pilot zone, ceramic coatings, or additional cooling airflow.

d. <u>Ignition and Stability Tests</u> - The Concept 2 Rig Test No. 8 system also underwent limited ignition and stability tests prior to initial engine testing to ensure its compatibility with engine operation. The results of the test are shown in Figure 52. Stability tests were run with the valves both fully open and closed. Ignition points were run with the valves closed. All tests were made on pilot nozzles only.

Fuel/air ratios required for ignition tended to be 25 to 50 percent higher than the production configuration shown by the line in Figure 52. However, the Concept 2 combustor should be compatible with the engine start cycle, because the engine enrichment system results in ignition fuel/air ratios considerably above the line. Blowout fuel/air ratios were close to the current production values, and this configuration was considered to have adequate stability for initial engine operation. A note of interest was that the combustor had better stability with the valves open than closed. Apparently, the high degree of swirl in the valve-open position more than compensated for the leaner reaction zone.

No ignition or stability testing was performed on Concept 3 because of the similarities in the primary zones of Phases II and III. The only change was in the channel height upstream of the primary orifices, which would improve the relight and stability limits due to longer residence times. The data obtained in Phase II was on both sides of the required limits, and it was considered that the required performance could be achieved with normal development efforts.

C. - ENGINE TESTS

The main emphasis of Phase III was evaluation of the Concept 2 variable-geometry combustion system, on a Model TFE731-2 engine. In addition to gaseous and particulate emissions measurements, all facets of engine operation were to be undertaken to determine the compatibility of the Concept 2 combustion system with required engine performance levels. These test efforts were divided into three main areas: engine installation and initial testing; steady-state emissions and performance testing; and acceleration and deceleration testing. The procedures and facilities for each of these activities is described fully in Chapter II, Section F.2.

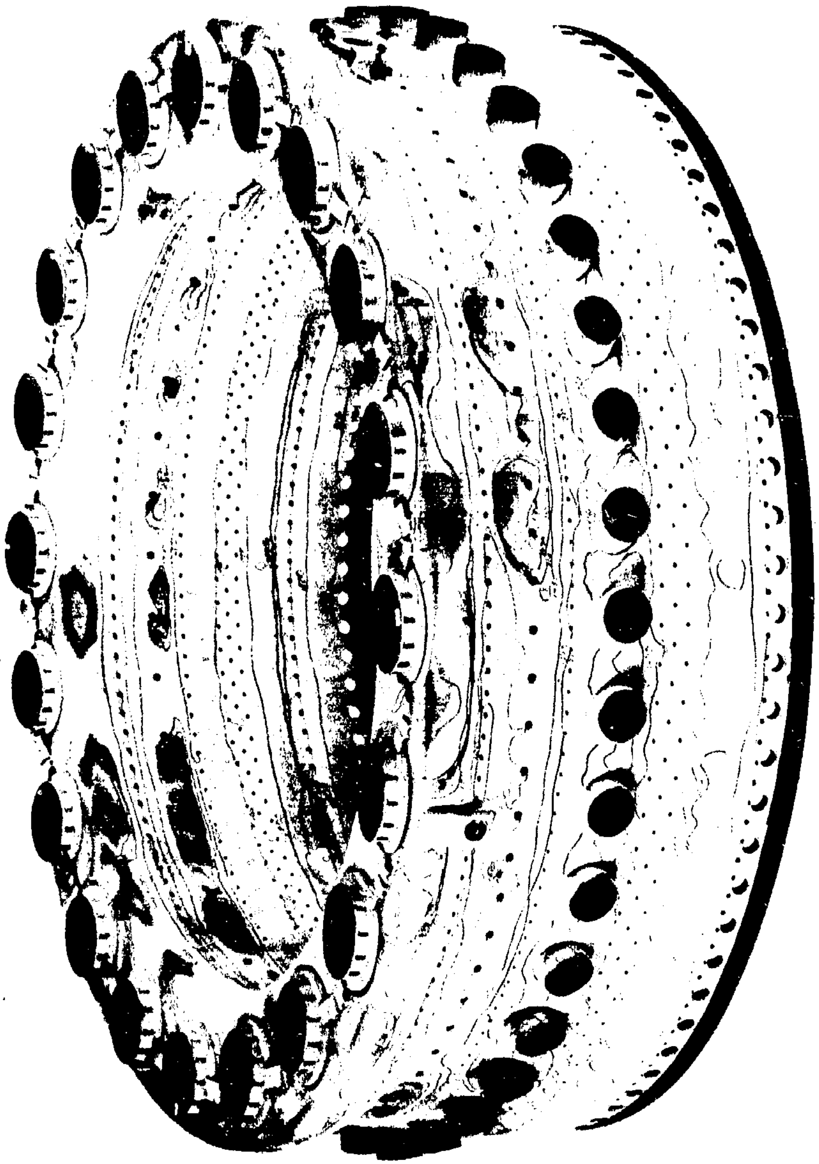

Figure 51. Concept 3, Test 2, Liner Temperatures, °F.

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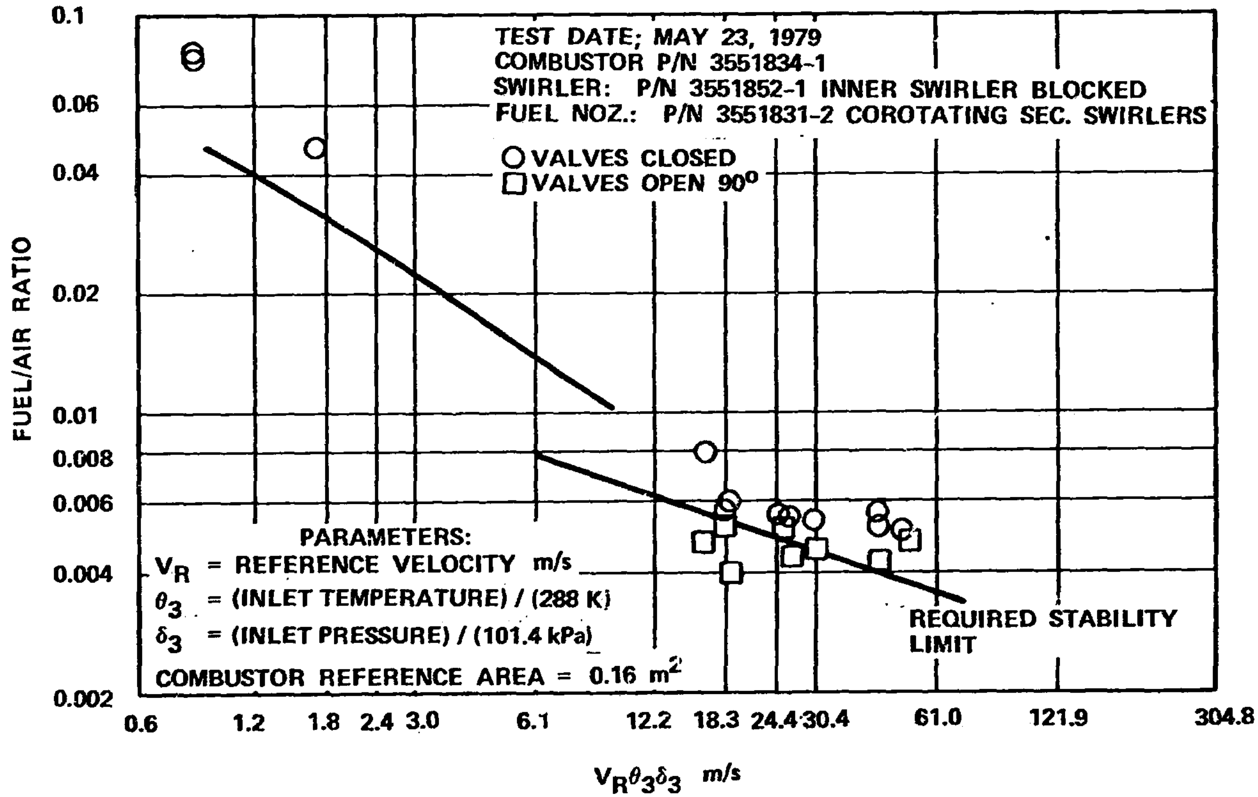

Figure 52. Ignition and Lean Stability Limits of the Concept II Combustor.

The final configuration tested produced the best overall emissions results, and these results are summarized below for the taxi-idle and takeoff points along with the program goals for comparison:

	Taxi-Idle EI		Takeoff EI	SAE
	HC g/kg fuel	CO g/kg fuel	NO_x g/kg fuel	Smoke No.
Concept 2	0.5	25.7	15.2	22.5
Program Goals	6.0	30.0	10.0	40.0

The Concept 2 system met the HC, CO, and smoke goals, but exceeded the goal for NO_x.

Table XIX is a description of the various modifications evaluated during the engine-test portion of the phase, and Figure 53 is a bar chart that shows the taxi-idle and takeoff emissions levels for the corresponding test numbers. In all, nine engine tests were performed; one during initial testing, and eight during steady-state emissions and performance testing. Two of the combustor configurations underwent acceleration and deceleration testing. A brief description of these tests and the test results is given in the following paragraphs. The complete test results are given in Appendix B.

1. Engine Installation and Initial Testing

The combustion system evaluated in Rig Test No. 7 was selected for Engine Test No. 1. The first step of the initial test was a trial assembly of this hardware with mating engine components and the required minor modifications to the engine and test cell hardware. These modifications are listed below:

- The fuel-flow divider valve was modified to phase in fuel flow to the airblast secondary nozzles at flows in excess of 113 kg/hr. This resulted in taxi-idle operation on pilots only.

- The Model TFE731-2 fuel pump was replaced with a Model ATF3-6 pump. This pump had outlet and inlet ports that connected to the variable-geometry actuator to supply motive pressure.

TABLE XIX. CONCEPT 2 ENGINE TEST CONFIGURATIONS.

Engine Test No.	Modification
1	Identical to Rig Test No. 7
2	Combustor swirlers were resealed to the dome (Repaired damaged seals) Removed blockage of combustor inner swirler
3	Fuel flow divider crack point reset to 113 kg/hr
4	80 0.56-cm diameter orifices added to the dilution zone
5	The pilot nozzles were changed from a flow number of 1.0 to 0.7 The 80 0.56-cm diameter orifices added in the previous experiment were enlarged to 0.89 cm diameter The outer swirlers were changed from a 60-degree vane angle configuration to 45 degrees which increased the effective flow area The combustor outer diameter was increased to improve the seal with the outer transition liner
6	The orifices for cooling air for the outer primary panel were reduced by one-third The dilution zone effective area was increased by 165 percent by slotting the existing orifices
7	The dilution zone area was decreased in order to return the combustor pressure drop to five percent The primary orifices were reduced in diameter to keep the primary zone equivalence ratio the same as in the previous configuration
8	Blocked half of the primary orifices Increased pilot nozzle spray angle 15 degrees to 85 degrees
9	All primary orifices blocked Total cooling orifice area of the first and second panels were reduced by 50 percent O.D. dilution orifices plunged

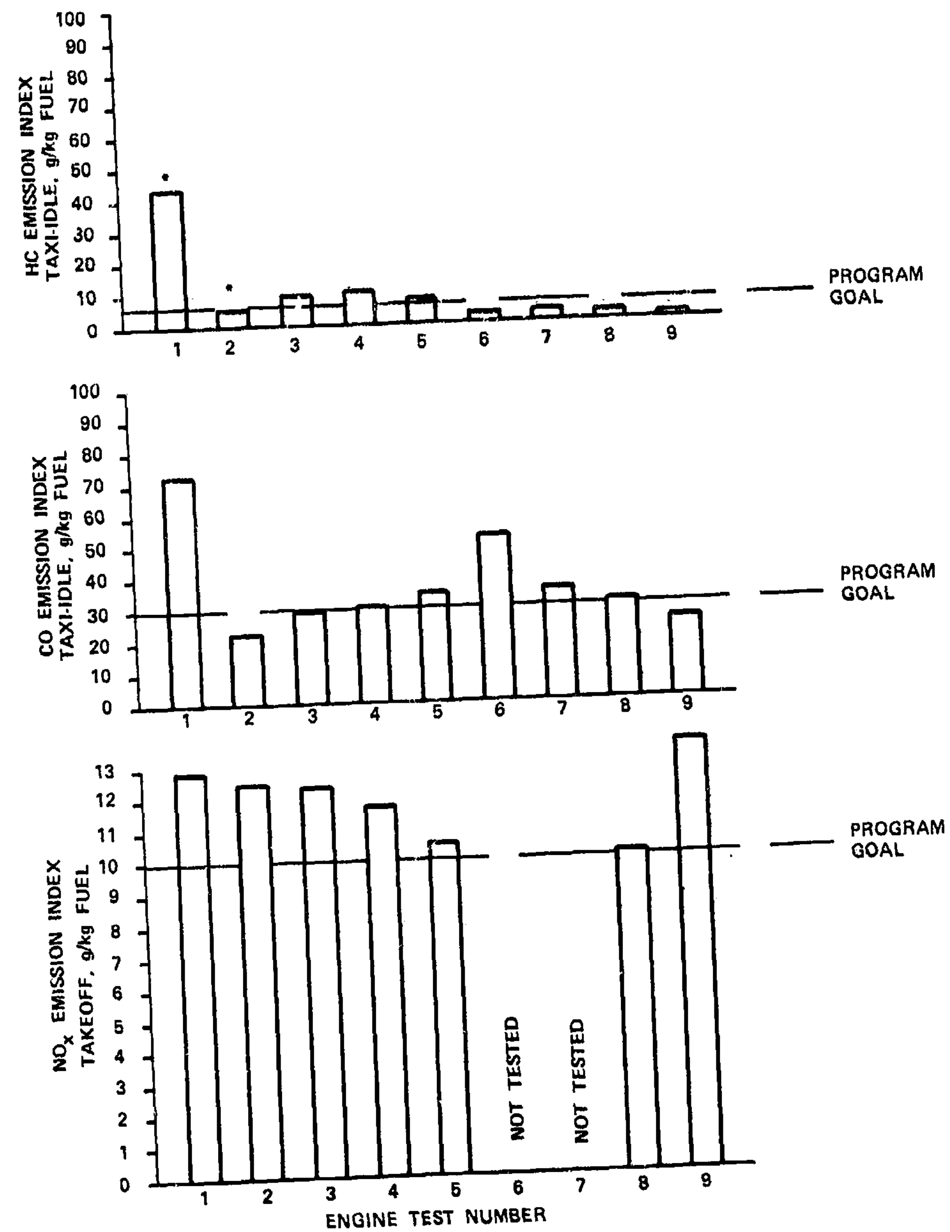

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Figure 53. Summary of Emission Results From Engine Tests.

a. Engine Test No. 1 - The first engine test (Test No. 1A and 1B) consisted of only low-power conditions to check out the engine and all the associated instrumentation and hardware. The test was interrupted to correct several minor problems, and then continued. Figure 54 shows the engine installed in the thrust stand with the emission probe in place. A close-up of the Concept 2 fuel manifolds and actuation system is shown in Figure 55.

Gaseous emissions data were taken at three power settings: taxi-idle, approach, and an intermediate setting. At taxi-idle, the run was made with the variable-geometry valves closed and on primary fuel only. At approach, seven valve angles were run; 0, 22.5, 30, 45, 60, 67.5, and 90 degrees. Fuel flow was through both circuits with the flow-divider crack point being 113 kg/hr. The third power setting run was at approximately 7.1 kN of thrust (indicated), and was limited by high engine vibration levels. The run was made with the valves at 90 degrees. Following this data scan, the valve position potentiometer became defective and would not indicate properly. Because of the high engine vibration and loss of valve-position indication, a decision was made to shut down.

At taxi-idle, the HC and CO values were 5.4 and 29.1 g/kg fuel, respectively (corrected to model pressure) which meets the program goals of 6.0 and 30.0 g/kg fuel. However, the fuel/air ratio (from emissions) was 0.0121, which is considerably higher than the model value of 0.0105, and a richer reaction would tend to produce lower levels of pollutants. Because of the high-ambient temperature (317 K), it was not possible to operate the engine near the model fuel/air ratio. The effect of ambient temperature on turbine engine performance is significant and above a certain temperature, the fuel/air ratio is high even when operating at reduced thrust levels. It was decided to rerun the taxi-idle data at night when the ambient temperature would be closer to standard-day conditions.

At approach, HC increased as the valve was opened from 0 to 90 degrees (0.1 to 1.5 g/kg fuel). However, there was a step increase between the 22.5- and 45-degree position. This same step increase appeared for CO, which varied from 3.0 to 21.3 g/kg fuel. The NO_x showed a reduction of 24 percent from the valve-closed to the valve-open position, with a 43- and 327- percent increase in HC and CO, respectively, over the same range. The approach data are shown in Figures 56 and 57 as a function of valve angle.

The engine was subsequently run again after the vibration problem was corrected as Engine Test No. 1B at taxi-idle and a data scan made. It was then accelerated to 100-percent available power for the prevailing ambient conditions (T_2 = 308 K). The valves were opened during acceleration. Following a data scan at 100-percent power, the engine was decelerated to 90, 75, and 50

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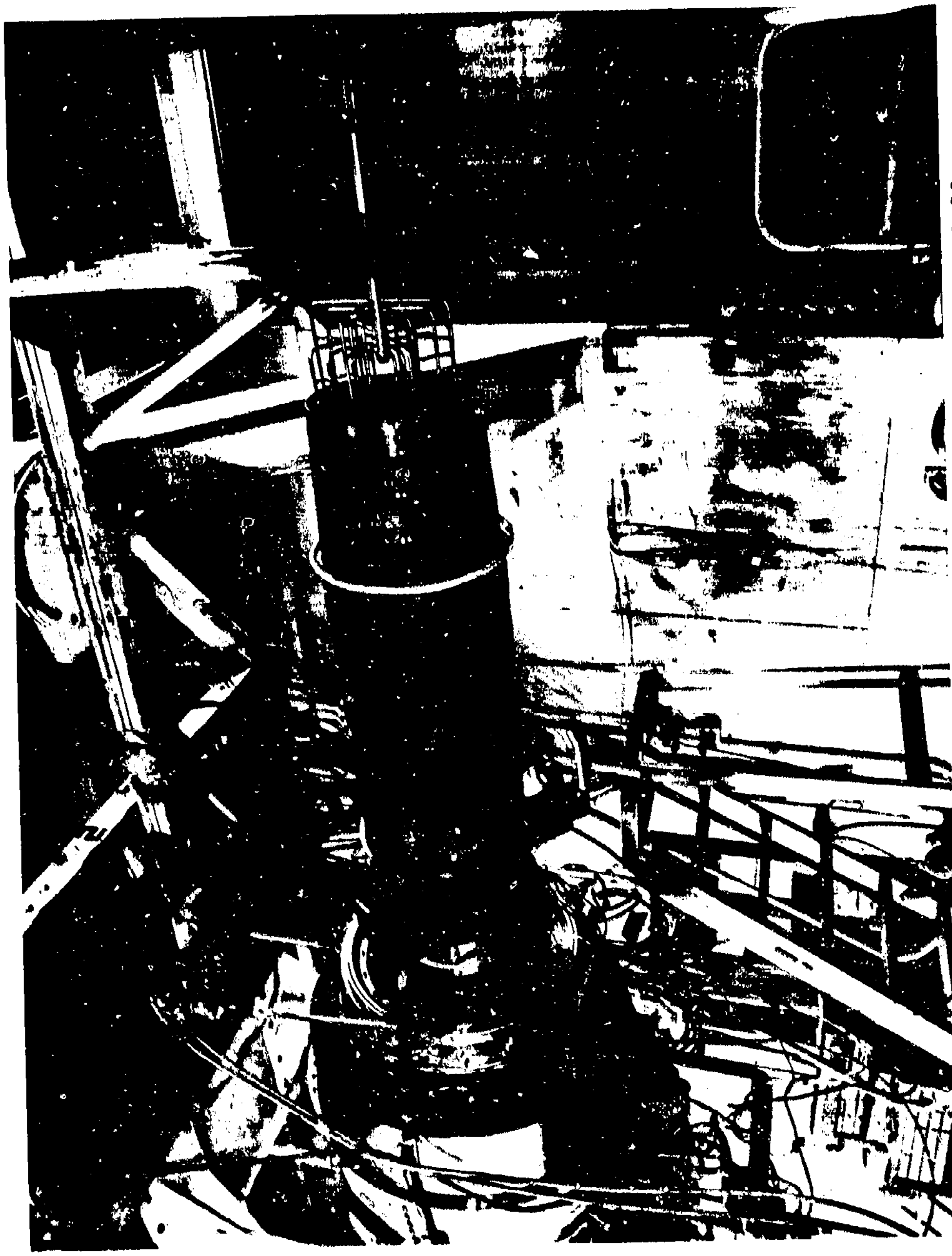

Figure 54. Model TFE731-2 Engine Installed in Test Cell.

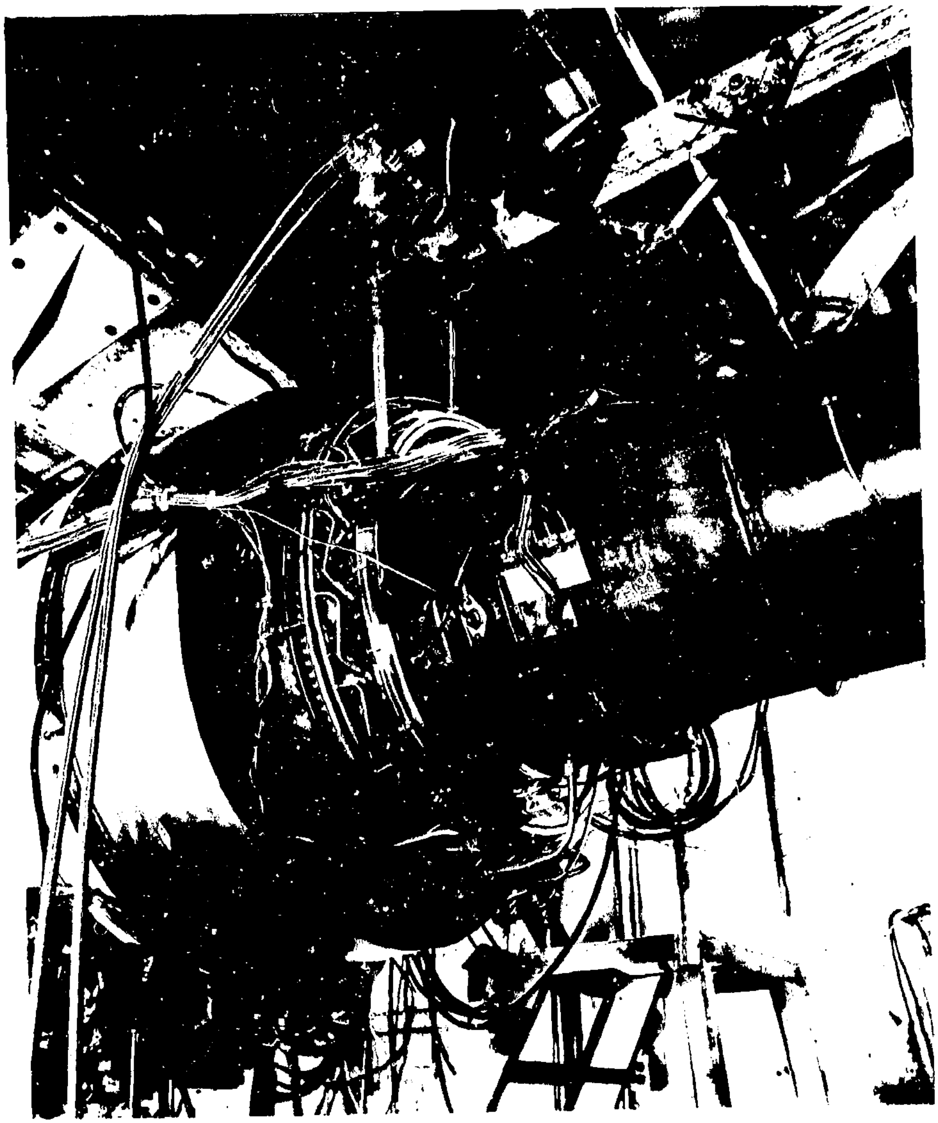

Figure 55. Concept 2, Fuel Manifolds and Actuation System.

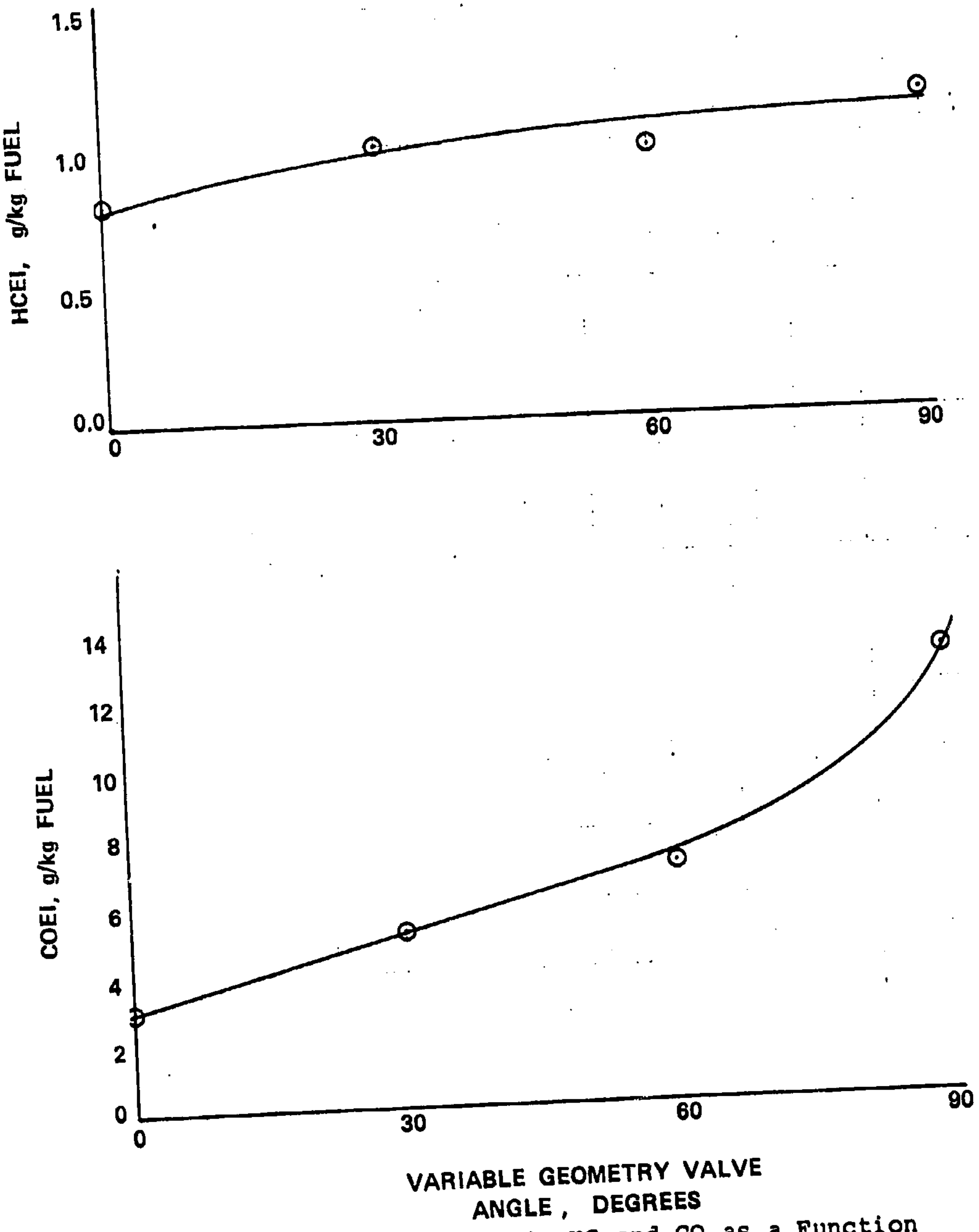

Figure 56. Variation in HC and CO as a Function of Valve Angle (S/N 7353 at Approach).

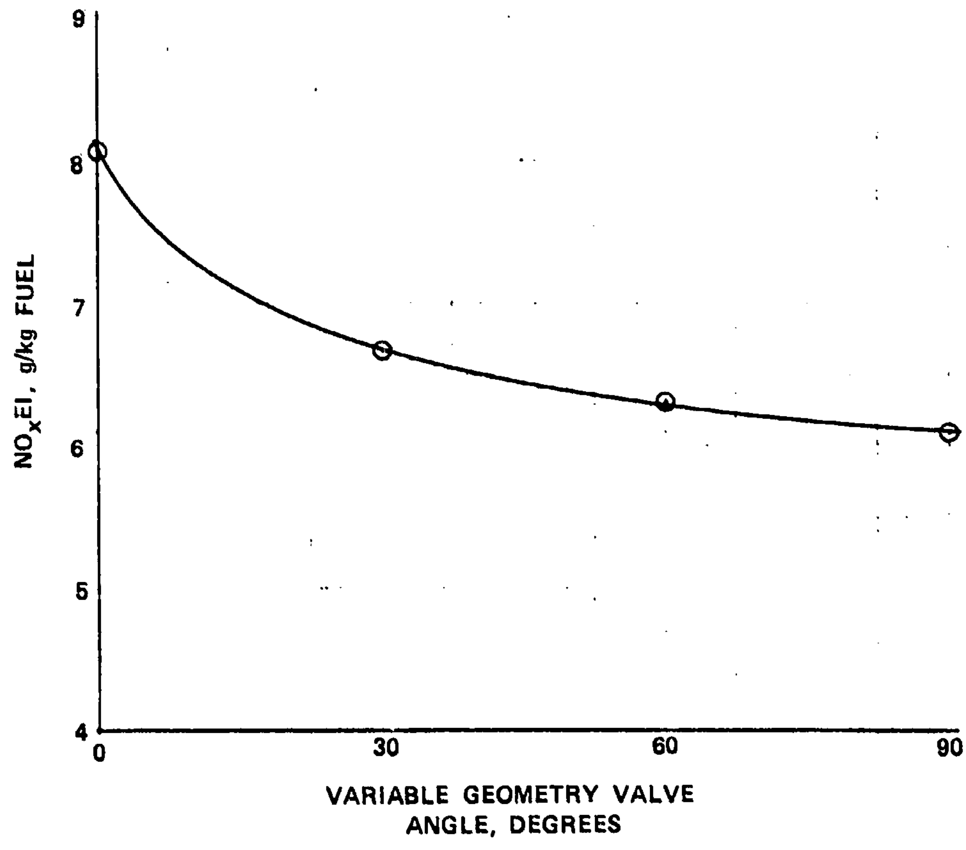

Figure 57. Variation in NO_x as a Function of Valve Angle (S/N 7353 at Approach).

percent, and approach with data scans made at each power setting. At approach, four valve settings were evaluated; 90, 60, 30, and 0 degrees. With the valves at 0 degrees the engine was decelerated to taxi-idle and another data scan made.

The taxi-idle data (corrected to model pressure) from this test showed an appreciable increase over the data from Engine Test 1A, as shown below:

	Taxi-Idle Emissions Indexes			
	HC g/kg fuel	CO g/kg fuel	F/A (emissions)	T_3 K
Engine Test 1A	5.2	29.1	0.0121	410
Engine Test 1B	42.9	72.7	0.0126	401
Engine Test 1B (repeat)	39.4	68.8	0.0115	407
Program Goals	6.0	30.0	0.0105	370

The similarities in fuel/air ratio and combustor inlet temperature would preclude a leaner reaction zone or hotter inlet temperature as the reasons for the HC and CO increases. A flow check of the pilot nozzles following engine disassembly showed the flows to be to specification with acceptable spray qualities. Inspection of the combustor interior revealed that two of the shimstock seals had been badly damaged, and several others had developed minor holes. Figure 58 shows the damaged seals. During rig testing, when these seals were installed to prevent air leakage between the combustor/swirler interface, the level was reduced by approximately 50 percent.

The data taken at the approach setting would tend to indicate that there was a significant change in the combustor operation between Engine Test 1A and 1B.

Figures 59 and 60 show that the HC and CO levels at approach, as a function of valve angle, changed dramatically between Engine Test No. 1A and 1B. The change appeared to begin between the 22.5- and 45-degree valve angle setting. It was felt that the dramatic increase in HC and CO at taxi-idle and approach from the two runs was a result of the deterioration of the combustor-swirler seals.

At the high-power setting, the corrected* NO_x was as follows:

*The values were corrected as explained in Chapter II, Section G.2.b, with a pressure exponent of 0.5.

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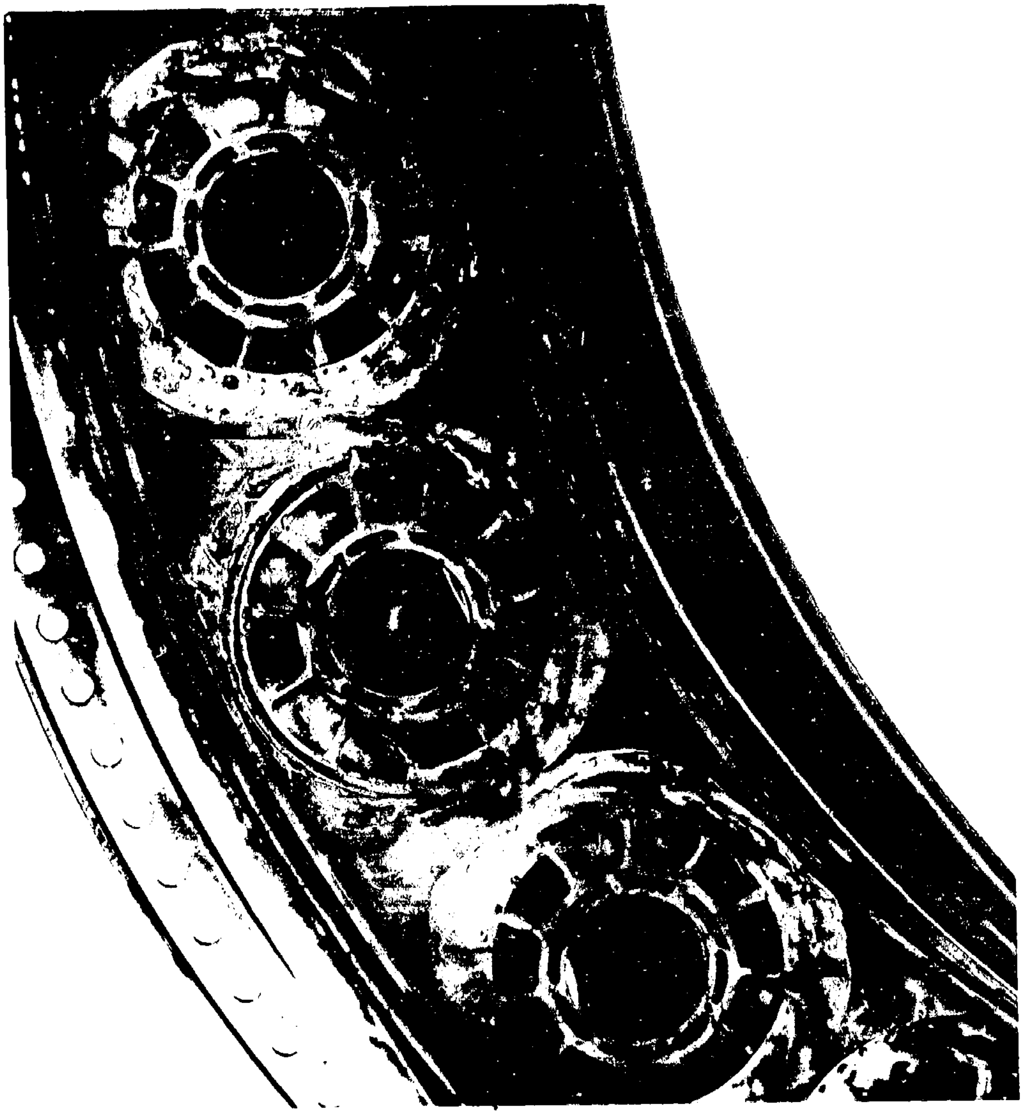

Figure 58. View Showing Damaged Seals.

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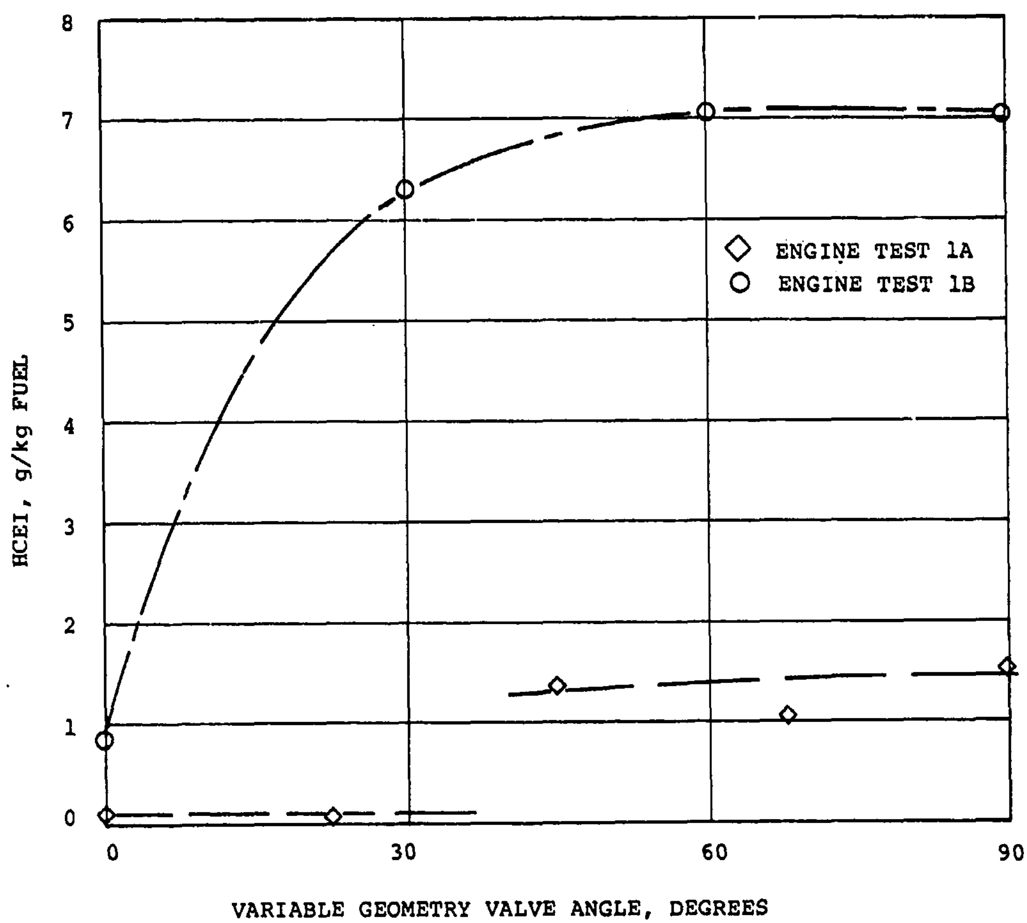

Figure 59. HC Emission Index Versus Valve Angle Setting.

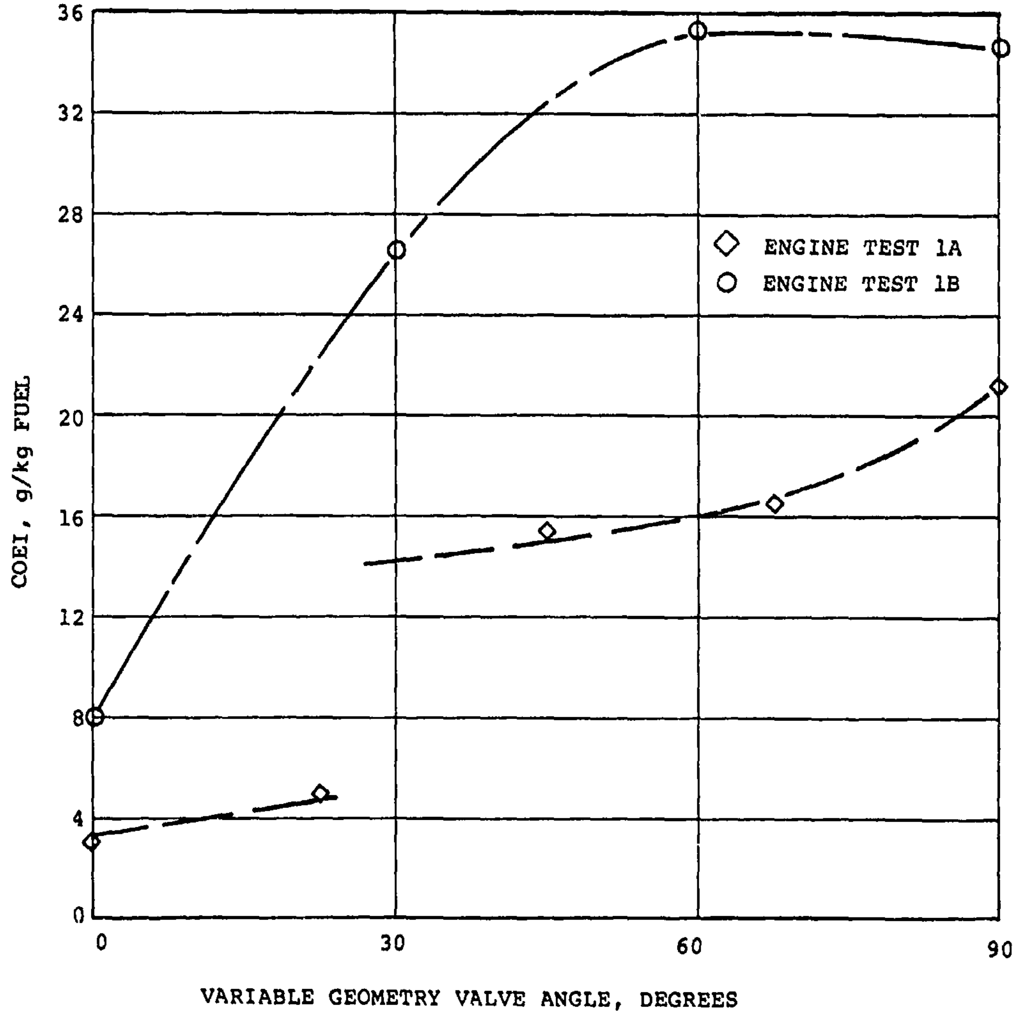

Figure 60. CO Emission Index Versus Valve Angle Setting.

	Climbout		Takeoff	
	NO_x EI g/kg fuel	F/A (emissions)	NO_x EI g/kg fuel	F/A (emissions)
Engine Test No. 1B	11.6	0.0152	12.9	0.0156
Rig Test No. 7	12.1	0.0146	13.8	0.0151
Program Goals	---	---	10.0	0.0154

In order for rig values to equal the engine values, the correction exponents to the ratio of rig-to-engine pressures would be 0.44 and 0.47 for climbout and takeoff, respectively.

The combustor had been painted with temperature-sensitive paint, and Figures 61 and 62 show typical inner and outer panel temperatures. The outer panels ran 866 to 950 K over most of the surface. The inner panels had two hot spots of 1200 K ; however, this was considered satisfactory for testing, and no wall-cooling development was undertaken.

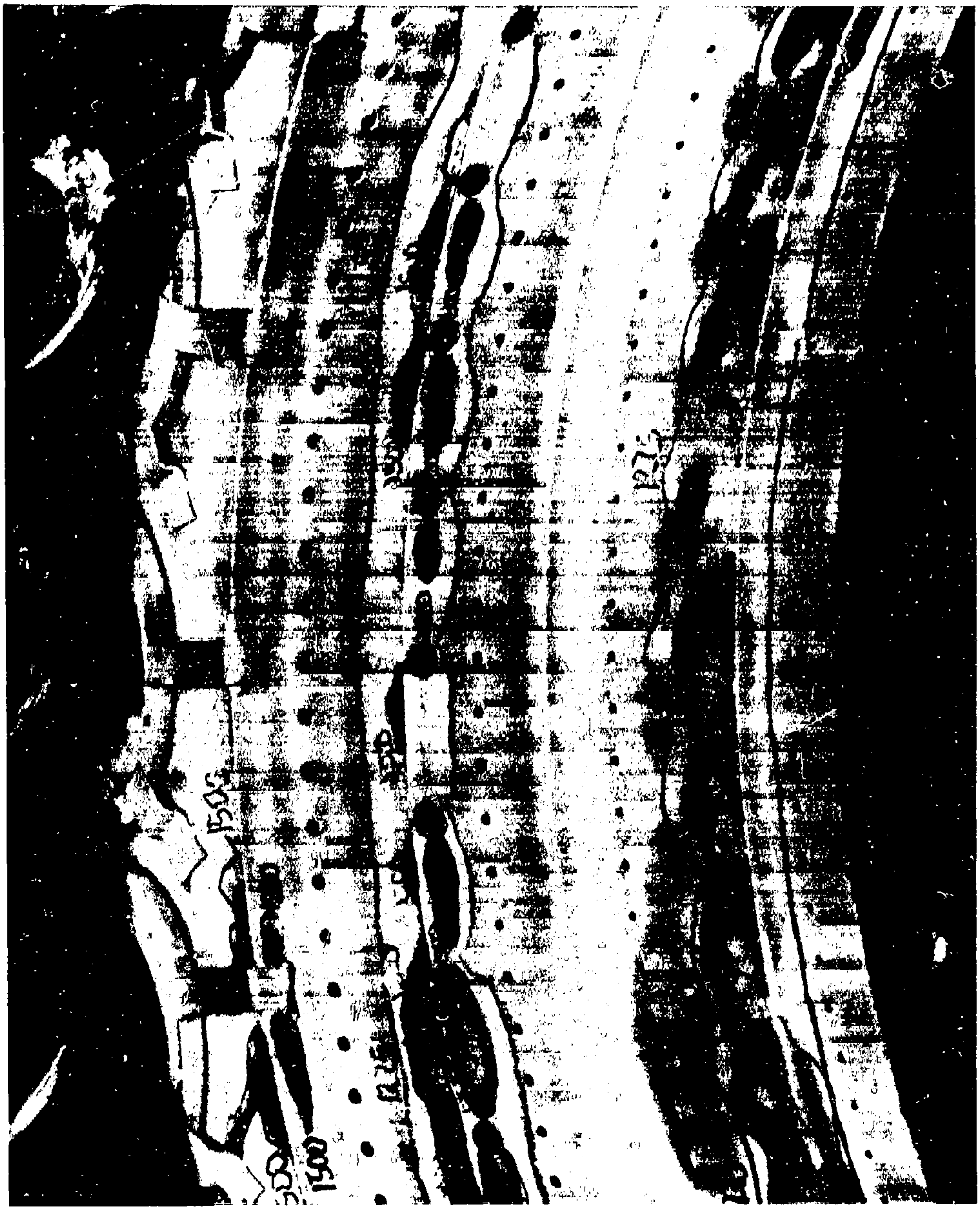

Figure 61. Inner panel Temperatures.

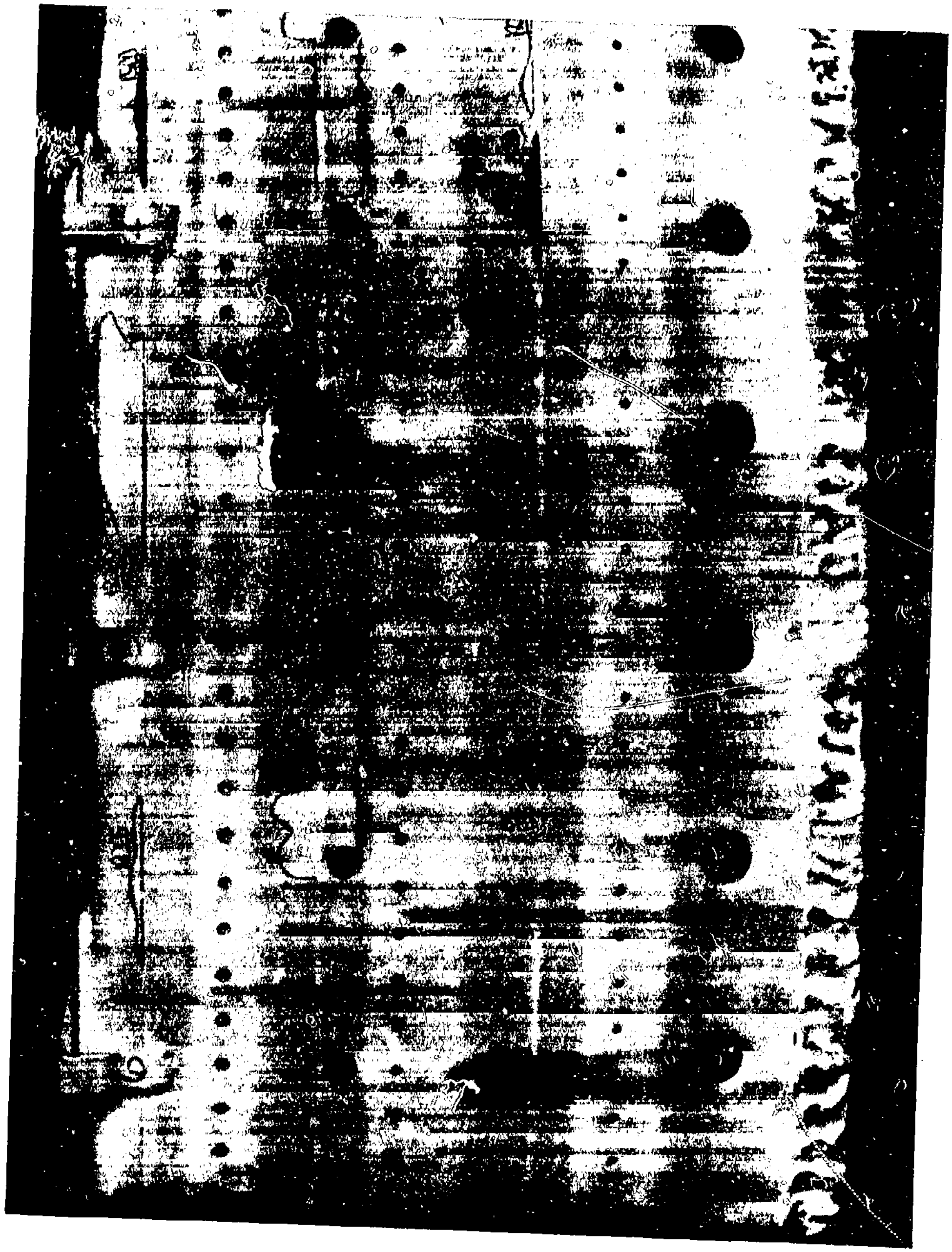

Figure 62. Outer Panel Temperatures.

MP-68907

b. <u>Engine Performance and Fan-Duct Correlation Test</u> - The test engine, S/N 7353, was built with the production combustion system and was tested with both the performance and mini-fan duct. The mini-fan duct was several feet shorter than the performance duct and accepted the variable-geometry actuation system without costly modification. The purpose of the test was to determine the performance level of the engine, and the magnitude of the performance reduction experienced with the mini-fan duct. These data were compared with engine test data with the Concept 2 combustion system using the mini-fan duct.

Both configurations were tested at six power settings (taxi-idle, 100-, 90-, 75-, 50- and 30-percent power). Performance and emissions data were taken at each power setting. With the standard performance duct, the engine interstage turbine temperature (Tt5) was 0.9 percent higher (at $N2/\sqrt{\theta}$ = 19,000 rpm) than the production requirements; however, TSFC was 0.2 percent lower than the requirements. In addition, the thrust-versus-N1 relationship for the engine was nearly the same as the average of 200 production engines. Therefore, the performance of this development engine was slightly below new production engine specifications, but adequate for development-test purposes.

A thrust reduction of 9.4 percent (at $N1\sqrt{\theta}$ = 19,000 rpm) was measured with the mini-fan duct compared with the performance fan ducts. With the Concept 2 combustor installed in the engine (also with mini-fan duct), a thrust reduction of 11.2 percent was recorded at the same N1 speed, compared with the standard fan duct. This 1 to 2 percent additional reduction in thrust may have been caused by the Concept 2 combustion system and/or instrumentation error. Although the Concept 2 pressure losses were equivalent to current Model TFE731 standard combustors, differences in radial temperature profile and resultant changes in turbine efficiencies may have caused part of the thrust reduction.

2. <u>Steady-State Emissions and Performance Testing</u>

a. <u>Engine Test No. 2</u> - Following Engine Test No. 1, the combustor was removed and the combustor-swirler seals replaced. Additionally, the washers that sealed the inner swirlers were removed to produce a leaner reaction zone at the high-power settings. Also, the fuel nozzles were sealed to the inner swirlers by the use of a high-temperature silicone rubber compound to prevent air leakage in the vicinity of the fuel nozzles.

This configuration underwent a brief rig test (Rig Test No. 8) at only the taxi-idle power setting prior to being installed in the engine.

The engine was tested for gaseous emissions over the full range of operating points. This involved running at the four LTO power settings, and five additional points. A 24-point sampling probe was used that could sample from two separate circuits of 12 sample points each. At the LTO power settings, samples were made with both 12-point circuits to determine stratification effects of the exhaust gases. At the other power settings the two circuits were combined, and only one sample from the 24 sample points was taken. Smoke measurement tests followed the gaseous emission test. Smoke was sampled at six power-setting points from taxi-idle to takeoff. Smoke measurements were made through both probe circuits for all power settings tested.

At the approach setting, a series of data points were taken at various angle setting of the combustor variable-geometry valves. During the gaseous emissions test, emissions were measured at valve angles of 0, 30, 60, and 90 degrees. For the smoke points only, valve angles of 0 and 90 degrees were set during the testing. Samples were taken through both probe circuits for all valve angles tested for both gaseous emissions and smoke.

At the taxi-idle setting (0.89 kN thrust) the following emission levels were measured:

	Taxi-Idle Emissions Indexes		
	HC g/kg fuel	CO g/kg fuel	F/A (emissions)
Engine Test No. 2	5.2	22.5	0.0119
Rig Test No. 8	3.3	21.9	0.0102
Engine Test No. 1B	42.9	72.7	0.0126
Program Goals	6.0	30.0	0.0105

Because of the relatively high ambient temperature (308 K) the fuel/air ratio at taxi-idle was above the engine model 288 K ambient value. Attempts to further reduce the fuel/air ratio by operating at a lower power setting (sub-idle point) actually increased the fuel/air ratio slightly.

At the climbout and takeoff points, the NO_X levels were essentially unchanged from the Engine Test No. 1B configuration, as shown below:

	Climbout NO_x EI g/kg fuel	Takeoff NO_x EI g/kg fuel
Engine Test No. 2	11.5	12.7
Engine Test No. 1B	11.6	12.9
Program Goal	-	10.0

Smoke measurements on the engine gave a smoke number of 25. This was well below the program goal of 40.

Engine Test No. 3 - The purpose of this test was to repeat the previous engine test with a colder ambient temperature in order to meet the required idle fuel/air ratio. The test configuration was identical to that of the previous test with one exception, the flow divider had been tested after engine Test No. 2 and found to have a crack point of 145 kg/hr, which was higher than desired. The crack point was reset to 113 kg/hr.

The initial testing was limited to the taxi-idle condition because of a malfunctioning digital acquisition system. The data did indicate that the combustion efficency did not meet the goal, and the flow divider was reset to a higher crack point (145 kg/hr) to ensure no fuel leakage from the secondary circuit.

The taxi-idle test points were repeated and results very similar to the initial data were obtained. A taxi-idle fuel/air ratio near the required value was obtained, because of the lower ambient temperature (289 K) and the use of the engine surge valve. The surge valve, which bleeds air from the LP compressor to prevent surge during transients, is normally open at idle and was closed during this testing to lower the engine fuel/air ratio. The taxi-idle condition results, corrected to standard pressure, were as follows:

	Taxi-Idle Emissions Indexes		
	HC g/kg fuel	CO g/kg fuel	F/A (emissions)
Engine Test No. 3 (surge valve open)	6.9	25.4	0.0115
Engine Test No. 2 (surge valve closed)	5.2	22.5	0.0119
Engine Test No. 3 (surge valve closed)	9.8	30.3	0.0108
Program Goals	6.0	30.0	0.0105

The results were comparable to Test No. 2 at the higher fuel/air ratio. At near the required fuel/air ratio, the CO emissions were close to the goal, but the HC was above the program goal.

The engine was tested over the entire operating range up to takeoff, and the NO_x values at the high-power points were as follows:

	Climbout		Takeoff	
	NO_x EI g/kg fuel	F/A (emissions)	NO_x EI g/kg fuel	F/A (emissions)
1. Engine Test No. 3	11.1	0.0147	12.4	0.0154
2. Engine Test No. 2	11.5	0.0147	12.7	0.0154
3. Program Goals	--	0.0147	10.0	0.0154

c. Engine Test No. 4 - In order to meet the HC goal, it was necessary to enrich the reaction zone at taxi-idle. This was accomplished by adding orifices to the dilution zone. Eighty 5.6-mm diameter orifices were added, which increased the total effective area of the combustor by 116 mm^2. The additional orifices increased the calculated reaction zone fuel/air ratio by 10 percent at taxi-idle.

The engine was tested over the entire operating range using the 24-point sampling probe. Sub-idle and rich-idle points were not tested and smoke was not measured, but tests were made at the taxi-idle point both with and without the compressor surge valve open.

At the taxi-idle point, the HC and CO emission levels were as shown below:

	Taxi-Idle Emissions Indexes		
	HC g/kg fuel	CO g/kg fuel	F/A (emission)
Engine Test No. 4,	10.6	32.4	0.0106
Engine Test No. 3,	9.8	30.3	0.0108
Program Goals	6.0	30.0	0.0105

The data indicated an increase in HC and CO levels from the previous test, even though the dilution-zone area had been increased by 29 percent.

A teardown inspection revealed that the combustor O.D. was undersized by 1.2 mm, which would have produced a leak path for the combustor air. However, this should have produced lower HC and CO levels, not higher.

The fuel nozzles were flow checked and the difference between maximum and minimum flow rates was found to be 20 percent of the maximum flow rate. This was considerably above the allowable variation of 10 percent. Additionally, a slight amount of streaking was observed on several of the nozzles.

d. Engine Test No. 5 - The following modifications were made in the variable-geometry combustion system for the Engine Test No. 5 configuration:

- o The pilot nozzle tips were changed from a flow number of 1.0 to 0.7 to improve atomization at taxi-idle.
- o The dilution orifices were enlarged from 5.6- to 8.9-mm diameter, which increased the dilution area 40 percent.
- o The outer swirlers (60-degree vanes) were replaced by increased airflow swirlers (45-degree vanes) to maintain the existing primary-zone equivalence ratio at high-power settings. The change in vane angle was required to increase the swirler effective area.
- o The combustor outer diameter was increased for a better seal with the outer transition liner to minimize air leakage.

The engine was tested over the entire operating range, including sub- and rich-approach with the combustor valves being cycled from 0 to 90 degrees open. Smoke was also measured.

At the taxi-idle point, the HC and CO emission levels were as shown in the following table:

	Taxi-Idle Emissions Indexes		
	HC g/kg fuel	CO g/kg fuel	F/A (emissions)
Engine Test No. 5, 0.89 cm diameter dilution orifices	6.5	35.9	0.0106
Engine Test No. 4, 0.56 cm diameter dilution orifices	10.6	32.4	0.0106
Engine Test No. 3, no additional dilution orifices	9.8	30.3	0.0108
Program Goals	6.0	30.0	0.0105

A reduction in HC emissions was achieved, but CO, NO_x, and smoke emissions increased. Raising the primary-zone equivalence ratio and improving the atomization were the probable reasons for the improvement in HC emissions.

The increase in CO emissions was attributed to inadequate sealing between the combustor and swirler; raising the equivalence ratio by decreasing the primary-zone airflow (and therefore increasing the residence time) should not have increased CO levels. The sensitivity of the CO emissions levels to quenching by air leaking around the swirlers was evidenced by an increase in the CO index at taxi-idle from 36 to 42 g/kg fuel in a second data point taken after the seals were damaged by running at takeoff power.

The primary-zone equivalence ratio at takeoff (0.4) was the same for Engine Test No. 5 as for the baseline test on Engine Test No. 3 because of the increased airflow through the 45-degree swirlers. Therefore, the increased NO_x and smoke number are attributed to the 45-degree swirl produced by the new swirlers.

The combustor had been painted with temperature-sensitive paint, and was 978 K or less on the outer liner and most of the inner liner. Near the inner primary orifices, 1200 K hot spots did appear, probably due to flameholding near the primary jets.

e. <u>Engine Test No. 6</u> - The following modifications were made in the variable-geometry combustion system prior to Engine Test No. 6.

- o The combustor swirlers were more securely attached to the combustor dome to prevent seal leakage and/or loss.
- o The cooling on the outer liner first skirt was reduced by one-third to increase efficiency at taxi-idle.
- o The dilution-zone area was increased further by slotting the orifices to enrich the primary zone--again to increase efficiency at taxi-idle. The dilution-zone effective area was increased by 165 percent.

The engine was tested at rich and normal taxi-idle, and was terminated because of high CO values. The results are shown below:

	Taxi-Idle Emissions Indexes		
	HC g/kg fuel	CO g/kg fuel	F/A (emissions)
Engine Test No. 6 slotted dilution zone	2.7	53.1	0.0104
Engine Test No. 5 0.89 cm dilution orifices	6.5	35.9	0.0106
Program Goals	6.0	30.0	0.0105

The increase in CO could have been caused by the reduced pressure drop (3.5 percent) of the Engine Test No. 6 configuration, compared with the Engine Test No. 5 configuration (4.5 percent, calculated). However, the HC emissions would also have been adversely affected by a lower pressure drop and less mixing, but were not. Another possible explanation is that enriching the primary zone had increased the thermal loading on the high temperature silicone rubber compound and shim stock sealing the swirler to the combustor. This may have caused the silicone rubber compound to be destroyed more rapidly than in previous tests, and the seals would have begun to leak shortly after light-off. During teardown following the test, it was found that the seals had been destroyed on several swirlers, which had not been observed on previous taxi-idle only tests. The HC emissions should also have been increased if the seals were inadequate, but previous tests have shown that HC emissions are less sensitive than CO to airflow leakage around the swirler.

f. Engine Test No. 7 - The following modifications were made in the variable-geometry combustion system prior to Engine Test No. 7.

- The dilution area was decreased in order to return the combustor pressure drop to 5 percent.
- The primary orifices were decreased to 3.2-mm diameter to maintain the primary-zone equivalence ratio at 0.8, and reduce quenching due to the primary jets.

The engine was tested from taxi-idle to rich approach. No further testing was done because digital data acquisition and hardware problems delayed the test until the ambient temperature was too high to obtain the model fuel/air ratio at taxi-idle.

	Taxi-Idle Emissions Indexes		
	HC g/kg fuel	CO g/kg fuel	F/A (emissions)
Engine Test No. 7 reduced primary orifices	3.0	35.1	0.0102
Engine Test No. 6 slotted dilution zone	2.7	53.1	0.0104
Engine Test No. 5 0.89-cm diameter dilution orifices	6.5	35.9	0.0106
Program Goals	6.0	30.0	0.0105

The HC index remained near the low value achieved in the prior test and the CO level returned to the lower levels achieved in previous tests (35.1-g/kg fuel at taxi-idle). Reducing the primary orifice diameter was ineffective in controlling quenching of CO. A probable reason is that the reaction could have been occurring near the liner walls, and the 2.5-cm penetration (calculated) of the primary jets was still sufficient to cause quenching.

g. Engine Test No. 8 - A detailed review showed that the Phase III airblast fuel nozzles had a fuel spray cone angle 15 degrees narrower than that of the Phase II pressure atomizers. The angle was measured under simulated taxi-idle conditions. Fuel nozzle spray angle can have a significant effect on emissions if the fuel droplets are not so small that they simply follow the airflow. The piloted airblast nozzles were sent back to Delavan, and the spray angle was increased by 20 degrees (to 85 degrees) by increasing the spray angle of the pilot nozzle tip and enlarging the nozzle-swirler discharge area. In addition, the primary orifices in between the swirlers were removed in order to reduce quenching of the taxi-idle reaction.

The engine was tested from taxi-idle to approach with the swirler valves closed, and from sub-approach to takeoff with the valves fully open. The taxi-idle results are given below:

	Taxi-Idle Emissions Indexes		
	HC g/kg fuel	CO g/kg fuel	F/A (emissions)
Engine Test No. 8	1.9	33.7	0.0105
Engine Test No. 7	3.0	35.1	0.0102
Program Goals	6.0	30	0.0105

The CO index at taxi-idle was reduced to very close to the goals, but the CO index at approach (18.4 g/kg fuel) increased substantially above previous test results (8.0 g/kg fuel). The EPAP's calculated from the test data are given below. As shown, the CO EPAP is not close to the goals in spite of the low values at taxi-idle.

	EPAP (lb/1000 lb thrust-hr/cycle)		
	HC	CO	NO_X
Engine Test No. 8	0.5	11.3	3.9
Program Goals	1.6	9.4	3.7

Because of the increased CO at approach, the taxi-idle CO emissions must be reduced to below the previous goal of 30 g/kg fuel in order to meet the required EPAP.

The effect of removing half of the primary orifices should have been to increase NO_X emissions due to increased residence time. However, improved fuel-air mixing caused by the larger fuel-nozzle spray angle was more dominant, and NO_X therefore decreased. The NO_X EPAP of 3.9 (see above) was one of the lowest achieved in Phase III. The measured smoke number of 30 was much improved over previous results, and was also probably due to the larger fuel-nozzle spray angle.

Liner temperatures were determined subsequent to the engine test to be generally below 980 K, with some hot regions (1090 K) on the inner liner near the primary orifices.

h. Engine Test No. 9 - The following modifications were made to reduce CO quenching in the combustor prior to Engine Test No. 9:

- The primary orifices were completely blocked
- Half of the cooling airflow was removed from the first and second panels on both the inner and outer liners
- The outer rows of dilution orifices were changed from flush to plunged by the insertion of grommets in order to minimize the distance that the jets travel upstream toward the primary zone.

The combustor was also instrumented with 14 thermocouples to supplement the temperature-sensitive paint to measure liner temperatures.

	Taxi-Idle Emissions Indexes		
	HC g/kg fuel	CO g/kg fuel	F/A (emissions)
Engine Test No. 9	0.3	28.3	0.0105
Engine Test No. 8	1.9	33.7	0.0105
Program Goals	6.0	30	0.0105

The CO level at taxi-idle was reduced sufficiently so that the CO EPAP goal was achieved in spite of a further increase in the CO level at approach (22 g/kg fuel). The EPAP's calculated for this test are given below:

	EPAP (lb/1000 lb thrust-hr/cycle)		
	HC	CO	NO_x
Engine Test No. 9	0.2	9.2	5.06
Engine Test No. 8	0.5	11.3	3.9
Program Goals	1.6	9.4	3.7

The removal of all of the primary orifices decreased quenching at the taxi-idle mode, but it also lengthened the residence time at the takeoff mode. The increase in reaction time was sufficient to increase the NO_x emissions from the previous level (an EPAP of 3.9) which was near the goal to a level comparable to that of production engines (an EPAP of 5.06) in spite of the lean primary zone at takeoff.

The reduction in cooling airflow produced numerous hot regions (1090 K) on the inner liner on the first and second panels. The thermocouples recorded a peak temperature of 1138 K on the inner liner. The outer liner was below 980 K on the majority of the liner surfaces.

The reduction in quenching lowered the smoke emissions to 22.5, significantly below the visability limits (40).

3. Acceleration and Deceleration Testing

Two Concept 2 combustion system configurations underwent acceleration and deceleration testing--Engine Tests No. 2 and No. 5. The procedure for these tests is fully described in Chapter II, Section F.2.

a. Engine Test No. 2 - The acceleration test was performed from the taxi-idle point and also from the 15-percent power point (as required by the FAA). In both cases the variable-geometry valves were cycled manually from closed to open at approximately the approach thrust level (30-percent thrust). There is a 5-second acceleration time limit when starting from 15-percent speed and the engine met this requirement.

The engine also met the 7-second deceleration requirement. The variable-geometry valves were manually cycled from open to closed as the engine passed through the approach thrust level.

b. Engine Test No. 5 - The test procedures and results were identical to the previous results. The engine met the 5-second acceleration requirements when accelerated from the 15-percent power point. The 7-second deceleration requirement was also met.

D. ASSESSMENT OF EMISSIONS RESULTS

Significant reductions in combustion-chamber emission levels were demonstrated during Phase III. The majority of the Concept 2 results were attained under actual engine tests, and the Concept 3 results were measured entirely during rig tests. The emissions reductions were, in both cases, attained without the loss of combustor performance; but both concepts do represent an increase in the degree of complexity over the present Model TFE731-2 production combustion system.

1. Concept 2 - The first two engine tests were run with high ambient temperatures, which resulted in the taxi-idle points being run at fuel/air ratios that were considerably higher than the engine model. The HC and CO levels were quite low, and it was originally felt that, although the low-power emissions would increase somewhat with decreasing fuel/air ratio, they would still be below the program goals. This did not prove to be the case. Engine Test No. 3 was the first configuration to run at the proper taxi-idle fuel/air ratio, and this produced EPAP's as shown below:

	EPAP (lb/1000 lb thrust-hr/cycle)			SAE
	HC	CO	NO_x	Smoke
Engine Test No. 3	2.58	8.72	4.17	25
Program Goals	1.6	9.4	3.7	40

Subsequent modifications, as listed in Table XX, were made to enrich the primary zone and consequently reduce HC emissions by enlarging the dilution area. Other modifications to reduce HC emissions incorporated improvements in the pilot-nozzle atomization and a reduction in the airflow on one primary cooling panel. During the testing of these modifications in Engine Tests No. 4, 5, and 6, the CO was found to be high. The primary orifices were reduced and finally eliminated to lessen CO quenching during the subsequent engine tests. In addition, the fuel-nozzle spray angle was increased 15 degrees in Engine Test No. 8 to improve efficiency, and all cooling in the primary zone was reduced by one-half to further reduce CO quenching in Engine Test No. 9. The elimination of all primary orifices to reduce CO emissions was the cause for the increased NO_x levels in Engine Test No. 9. This configuration met the goals for HC, CO, and smoke, but was high on NO_x.

TABLE XX. EFFECTS OF ENGINE MODIFICATIONS ON THE EPA PARAMETERS

Engine Test No.	EPAP (lb/1000 lb thrust-hr/cycle) HC	CO	NO_x	SAE Smoke
3 (Baseline)	2.6	8.7	4.2	25
4	2.8	9.2	4.1	--
5	1.7	10.9	4.3	44
6	Tested at taxi-idle only			
7	Tested at taxi-idle only			
8	0.5	11.3	3.9	30
9	0.2	9.2	5.1	22.5
Program Goals	1.6	9.4	3.7	40.0

2. Concept 3 - Emissions levels below the goals were demonstrated in Phase III with a staged combustion system much less complex than the premix designs of Phases I and II. The reductions in NO_x emissions were not as high as achieved in Phase II because of the elimination of the premixing; however, the Phase III NO_x levels were within the goals of the program. The Test 3 Phase III results are compared to the best results of Phase I and II below. The rig results were adjusted by the procedures outlined in Chapter II.

EPAP
(lb/1000 lb thrust-hr/cycle)

Concept 3 Configurations					
Pollutant	Program Goal	Phase I	Phase II	Phase III Air-Assist	Phase III No Air-Assist
HC	1.6	0.5	0.6	0.5	0.5
CO	9.4	8.3	7.6	8.2	8.2
NO_x	3.7	2.7	2.9	3.5	3.8

The Phase III results are presented with and without 345 kPa air-assist differential pressure and with 80-percent main stage fuel flow at takeoff and climbout (the 80-percent main stage fuel flow at climbout was not run without air assist, but was estimated by similar data at takeoff). The main stage fuel flow was 1-percent of the total at the approach condition. No air assist was necessary at taxi-idle. The SAE smoke number was 9.5 measured at one-third of the engine pressure at the climbout condition, and 14 at the approach condition at actual engine pressure with 10 percent main fuel flow. It is believed that the smoke goal of 40 was attained at the climbout condition, but only a test at full engine pressure could verify this.

Rapid engine acceleration would probably require a full main stage fuel manifold at the approach condition. The maximum main stage fuel flow that could be staged at approach while maintaining low CO levels was 1 percent of the total fuel flow. If staging of this amount is found to be impractical, integral pressurizing valves could be used to fill the main-stage manifold at approach or lower power settings.

The amount of fuel-air mixing achieved in the main stage with pressure atomizers was not adequate to meet the NO_x requirement without the use of air assist. However, it is believed that airblast nozzles used in the main stage would eliminate the need for air assist. The staged configuration that would give the best emissions results would be the same as the Test No. 3 configuration, except dual-orifice pressure atomizers would be required in the pilot zone and airblast nozzles in the main stage.

CHAPTER IV
CONCLUDING REMARKS

The results contained in this report document the activity conducted under the third phase of a three-phase program entitled Pollution Reduction Technology Program for Small Jet Aircraft Engines (Class T1). The overall objective of this program was to identify, develop, and demonstrate techniques capable of reducing emissions of unburned hydrocarbons, carbon monoxide, oxides of nitrogen, and smoke to levels below the standards which had been proposed for implementation in 1979 by the Environmental Protection Agency. The EPA standards were subsequently amended for T1 class engines, however, the emissions levels originally proposed by the EPA remained as goals for this program. The combustion system from the AiResearch Model TFE731-2 Turbofan Engine was the baseline design for the program effort. The constraints placed upon the designs were that emissions reductions be obtained with no deterioration in combustion performance or durability levels, and with no changes to the engine envelope.

The Phase I program identified three conceptual approaches that involved increasing degrees of developmental complexity towards meeting the emissions goals. These approaches included advanced modifications to the existing Model TFE731-2 combustion system, a variable-geometry combustion system using airblast fuel injectors, and a premix/prevaporization combustion system with axially-staged fuel injection (identified as Concepts 1, 2, and 3, respectively). Combustion rig screening testing was conducted in Phase I to narrow down the candidate approaches to the best two. The Concept 2 variable-geometry system and Concept 3 premix/prevaporization systems were chosen to undergo further combustion rig development in Phase II. Phase I testing revealed that for Concept 2 at least two-position variable airflow to the fuel nozzle air swirlers was necessary to meet all emissions levels.

The purpose of Phase II testing was to develop the selected combustion systems through iterative rig testing to obtain combustion hardware, operation and performance that were compatible with the TFE731-2 engine. In addition, two engine tests with rig-adapted hardware were provisioned for the purpose of obtaining engine-to-test rig emissions correlations. During Phase II one combustion system, the Concept 2 variable-geometry system, was identified as having the most potential for meeting the program goals in a time-effective manner in that it would require the least amount of development to ensure engine geometric and operational compatibility. The development of the variable-airflow system continued in Phase II. Test results indicated that all emissions were close to the program goals.

The Phase III program involved engine testing of the Concept 2 variable geometry design. The system was engine tested at various power settings from taxi-idle to takeoff under steady-state conditions and emissions and engine performance data were taken. Additionally, acceleration and deceleration tests were made to check conformance with FAA requirements. Prior to the engine tests, the system underwent limited rig testing to check performance compatibility with engine requirements. In addition, Concept 3, the axial staged fuel injection system also underwent limited rig testing.

The Concept 2 design produced engine test results which met the HC, CO and smoke goals but failed to meet the NO_X goal. In terms of engine performance, this system was considered compatible with the TFE731 engine and demonstrated satisfactory acceleration and deceleration characteristics, however, the combustion liner would require additional development to match the durability (life) of the present production combustor.

The test results demonstrated the feasibility of variable geometry devices to control the reaction zone equivalence ratio as a means of limiting emissions levels. The test data also indicated the sensitivity of the system to the fuel injector design and to the interface between the fuel injectors and the combustor. Small amounts of air leakage in the vicinity of the fuel injectors discharge produced order-of-magnitude increases in the HC and CO emission indices at the taxi-idle power settings. To a lesser degree, pollutant formation was also sensitive to spray quality. Limitations in the Concept 2 hardware prevented a totally satisfactory solution to the air-leakage problem and, although improvements were made with the fuel injectors, additional development could have produced further reductions in taxi-idle emission levels. Therefore, it was necessary to richen the reaction zone in order to meet the taxi-idle emission goals. However, this also produced a richer reaction zone at the high power setting which could not be compensated for by the available variable geometry hardware. This resulted in NO_X levels which exceeded the program goals.

It is recommended that for further variable geometry combustion system development the dome air swirlers be permanently attached to the dome and all air leak paths sealed. The fuel nozzles should also have a positive seal at the interface with the dome swirlers. Such devices as piston rings could be used which would allow for assembly tolerances and thermal expansion during operation. It is also recommended that, in addition to the swirler airflow, the combustor dilution air or the primary zone cooing airflow be controlled by variable geometry. This would allow a greater difference between the combustor primary zone equivalence ratios at taxi-idle and takeoff conditions and the attainment of a more nearly optimum equivalence ratio at each power setting. Also, quenching of the reaction at taxi-idle, due to increases in cooling airflow caused by the closing of the swirler valves, would be reduced. With these modifications, together with properly developed fuel injectors, it would be possible to meet the program taxi-idle CO and HC emissions goals with a somewhat leaner reaction zone, as has been demonstrated in previous phases. A greater contrast between low-power and high-power reaction-zone airflows would strongly enhance the probability of meeting the program NO_x emissions goals.

APPENDIX A

COMBUSTOR HOLE PATTERNS

OUTER LINER

ROW NUMBER	TYPE OF ORIFICE	NUMBER OF ORIFICES	DIAMETER cm	TOTAL AREA, cm^2	AIRFLOW, PERCENT OF INLET CONFIGURATION		
					A	B	C
1	Cooling	180	0.267	6.7	7.4	3.9	3.7
2	Primary	40	0.635	12.7	9.7	5.0	4.8
3	Cooling	180	0.206	6.0	4.2	2.1	2.0
4	Cooling	180	0.16	3.6	2.5	1.2	1.2
5	Dilution	--	--	--	--	--	--
6	Dilution	40	0.932	27.3	20.4	10.9	10.4

INNER LINER

ROW NUMBER	TYPE OF ORIFICE	NUMBER OF ORIFICES	DIAMETER cm	TOTAL AREA, cm^2	AIRFLOW, PERCENT OF INLET CONFIGURATION		
					A	B	C
7	Cooling	120	0.267	6.7	4.5	2.6	2.5
8	Primary	40	0.635	12.7	9.3	5.4	5.2
9	Cooling	120	0.206	4.0	2.75	1.6	1.5
10	Cooling	120	0.16	2.4	1.7	1.0	0.9
11	Dilution	--	--	--	--	--	--
12	Dilution	40	0.932	27.3	20.3	12.2	11.8
13	Cooling	120	0.16	2.4	1.7	1.0	1.0

A 3551852-1 swirlers closed, 13.3 cm^2, 7.4% airflow, airblast nozzles 11.6 cm^2, 6.9% airflow.

B 3551852-1 swirlers 45° open, 121.2 cm^2, 47.2% airflow, airblast nozzles 11.6 cm^2, 4.5% airflow.

C 3551852-1 swirlers 90° open, 129.7 cm^2, 49.25% airflow, airblast nozzles 11.6 cm^2, 4.4% airflow.

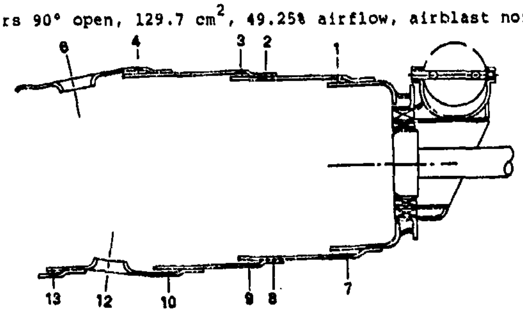

Figure A-1. Combustor Orifice Pattern, Concept 2, Rig Tests 1, 2, 3, and 4.

OUTER LINER

ROW NUMBER	TYPE OF ORIFICE	NUMBER OF ORIFICES	DIAMETER cm	GEOMETRIC AREA, cm^2	AIRFLOW, PERCENT OF INLET CONFIGURATION A
1	Cooling	180	0.267	6.7	7.6
2	Primary	40	0.635	12.7	10.0
3	Cooling	180	0.206	6.0	4.35
4	Cooling	180	0.16	3.6	2.6
5	Dilution	--	--	--	--
6	Dilution	40	0.932	27.3	20.9

INNER LINER

ROW NUMBER	TYPE OF ORIFICE	NUMBER OF ORIFICES	DIAMETER cm	GEOMETRIC AREA, cm^2	AIRFLOW, PERCENT OF INLET CONFIGURATION A
7	Cooling	120	0.267	6.7	4.6
8	Primary	40	0.635	12.7	9.5
9	Cooling	120	0.206	4.0	2.8
10	Cooling	120	0.16	2.4	1.7
11	Dilution	--	--	--	--
12	Dilution	40	0.932	27.3	20.9
13	Cooling	120	0.16	2.4	1.7

A 3551832-1 swirlers closed, 13.3 cm^2, 7.6% airflow, airblast nozzle 7.3 cm^2 (inner swirler blocked) 4.4% airflow.

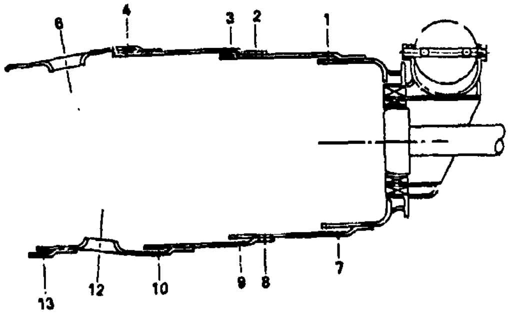

Figure A-2. Combustor Orifice Pattern, Concept 2, Rig Test No. 5.

OUTER LINER

ROW NUMBER	TYPE OF ORIFICE	NUMBER OF ORIFICES	DIAMETER, cm	GEOMETRIC AREA, cm^2	AIRFLOW, PERCENT OF INLET CONFIGURATION A
1	Cooling	180	0.267	6.7	8.0
2	Primary	40	0.635	12.7	10.45
3	Cooling	180	0.206	6.0	4.6
4	Cooling	180	0.16	3.6	2.7
5	Dilution	--	--	--	--
6	Dilution	40	0.932	27.3	22.0

INNER LINER

ROW NUMBER	TYPE OF ORIFICE	NUMBER OF ORIFICES	DIAMETER, cm	GEOMETRIC AREA, cm^2	AIRFLOW, PERCENT OF INLET CONFIGURATION A
7	Cooling	120	0.267	6.7	4.8
8	Primary	40	0.635	12.7	10.0
9	Cooling	120	0.206	4.0	3.0
10	Cooling	120	0.16	2.4	1.8
11	Dilution	--	--	--	--
12	Dilution	40	0.932	27.3	21.8
13	Cooling	120	0.16	2.4	1.8

A 3551852-1 swirlers closed 13.3cm^2, 7.9% airflow, airblast nozzles completely blocked.

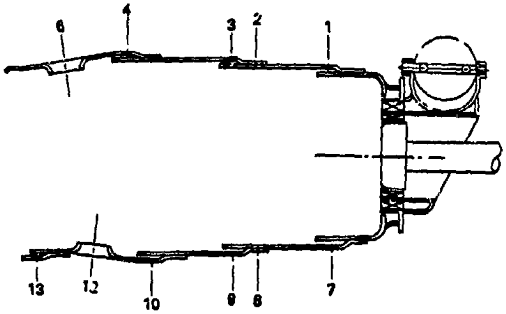

Figure A-3. Combustor Orifice Pattern, Concept 2, Rig Test No. 6.

OUTER LINER

ROW NUMBER	TYPE OF ORIFICE	NUMBER OF ORIFICE	DIAMETER, cm	GEOMETRIC AREA, cm^2	AIRFLOW, PERCENT OF INLET CONFIGURATION				
					A	B	C	D	E
1	Cooling	180	0.267	6.7	8.1	5.1	4.3	4.1	4.1
2	Primary	40	0.635	12.7	10.6	6.6	5.5	5.2	5.2
3	Cooling	180	0.206	6.0	4.7	2.8	2.3	2.2	2.2
4	Cooling	180	0.16	3.6	2.8	1.65	1.3	1.3	1.3
5	Dilution								
6	Dilution	40	0.932	27.3	22.4	13.9	11.8	11.3	11.3

INNER LINER

ROW NUMBER	TYPE OF ORIFICE	NUMBER OF ORIFICE	DIAMETER, cm	GEOMETRIC AREA, cm^2	AIRFLOW, PERCENT OF INLET CONFIGURATION				
					A	B	C	D	E
7	Cooling	120	0.267	6.7	4.9	3.25	2.8	2.7	2.7
8	Primary	40	0.635	12.7	10.1	6.7	5.8	5.6	5.6
9	Cooling	120	0.206	4.0	3.0	2.0	1.7	1.6	1.6
10	Cooling	120	0.16	2.4	1.8	1.2	1.0	1.0	1.0
11	Dilution								
12	Dilution	40	0.932	27.3	22.2	15.0	13.0	12.5	12.5
13	Cooling	120	0.16	2.4	1.8	1.2	1.1	1.0	1.0

A 3551852-1 swirlers closed, no airflow, airblast nozzle, 9.8 cm^2, 6.3% airflow
B 3551852-1 225 open, 76.3 cm^2 34.8% airflow, airblast nozzle, 9.8 cm^2, 4.5% airflow
C 3551852-1 45° open, 107.9 cm^2, 44.1% airflow, airblast nozzle, 9.8 cm^2, 4.1% airflow
D 3551852-1 67.5 open, 111.1 cm^2, 46.2% airflow, airblast nozzle, 9.8 cm^2, 3.9% airflow
E 90° open, 116.4 cm^2, 46.3% airflow, airblast nozzle, 9.8 cm^2, 3.9% airflow

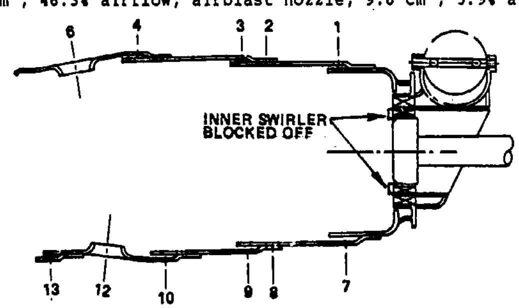

Figure A-4. Combustor Orifice Pattern, Concept 2, Rig Test No. 7 and Engine Test No. 1.

OUTER LINER

ROW NUMBER	TYPE OF ORIFICE	NUMBER OF ORIFICES	DIAMETER, cm	GEOMETRIC AREA, cm^2	AIRFLOW, PERCENT OF INLET CONFIGURATION			
					A	B	C	D
1	Cooling	180	0.267	6.7	7.5	4.3	4.0	3.8
2	Primary	40	0.635	12.7	9.8	5.5	5.2	4.8
3	Cooling	180	0.206	6.0	4.3	2.3	2.2	2.0
4	Cooling	180	0.16	3.6	2.6	1.35	1.3	1.2
5	Dilution	--	--	--	--	--	--	--
6	Dilution	40	0.932	27.3	20.6	11.8	11.2	10.5

INNER LINER

ROW NUMBER	TYPE OF ORIFICE	NUMBER OF ORIFICES	DIAMETER, cm	GEOMETRIC AREA, cm^2	AIRFLOW, PERCENT OF INLET CONFIGURATION			
					A	B	C	D
7	Cooling	120	0.267	6.7	4.5	2.8	2.7	2.6
8	Primary	40	0.635	12.7	9.4	5.8	5.6	5.3
9	Cooling	120	0.206	4.0	2.8	1.7	1.6	1.5
10	Cooling	120	0.16	2.4	1.7	1.0	1.0	0.9
11	Dilution	--	--	--	--	--	--	--
12	Dilution	40	0.932	27.3	20.6	13.1	12.5	11.9
13	Cooling	120	0.16	2.4	1.7	1.1	1.0	1.0

A 3551852-1 swirlers closed 13.3 cm^2, 7.5% airflow, airblast nozzles, 9.8 cm^2, 5.9% airflow
B 3551852-1 30° open, 109.4 cm^2 43.8% airflow, airblast nozzles, 9.8 cm^2, 4.0% airflow
C 3551852-1 60° open, 119.2 cm^2 46.7% airflow, airblast nozzles, 9.8 cm^2, 3.9% airflow
D 3551852-1 90° open, 129.7 cm^2 49.5% airflow, airblast nozzles, 9.8 cm^2, 3.8% airflow

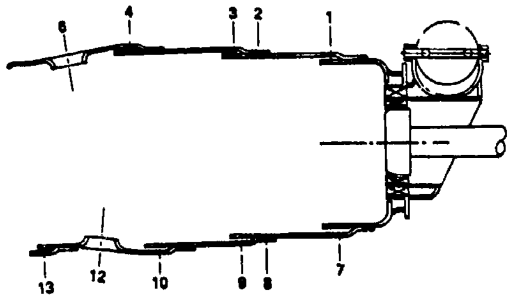

Figure A-5. Combustor Orifice Pattern, Concept 2, Rig Test No. 8 and Engine Tests 2 & 3.

OUTER LINER

ROW NUMBER	TYPE OF ORIFICE	NUMBER OF ORIFICES	DIAMETER, cm	GEOMETRIC AREA, cm^2	AIRFLOW, PERCENT OF INLET CONFIGURATION	
					A	B
1	Cooling	180	0.267	6.7	6.8	3.5
2	Primary	40	0.635	12.7	8.9	4.5
3	Cooling	180	0.206	6.0	3.9	1.9
4	Cooling	180	0.16	3.6	2.3	1.1
5	Dilution	40	0.559	9.8	4.4	2.5
6	Dilution	40	0.932	27.3	18.8	9.7

INNER LINER

ROW NUMBER	TYPE OF ORIFICE	NUMBER OF ORIFICES	DIAMETER, cm	GEOMETRIC AREA, cm^2	AIRFLOW, PERCENT OF INLET CONFIGURATION	
					A	B
7	Cooling	120	0.267	6.7	4.0	2.4
8	Primary	40	0.635	12.7	8.5	4.9
9	Cooling	120	0.206	4.0	2.5	1.4
10	Cooling	120	0.16	2.4	1.5	0.9
11	Dilution	40	0.559	9.8	4.4	2.7
12	Dilution	40	0.932	27.3	18.7	11.1
13	Cooling	120	0.16	2.4	1.5	0.9

A 3551852-1 swirlers closed 13.3 cm^2 6.9% airflow, airblast nozzles, 9.8 cm^2, 5.5% airflow

B 3551852-1 swirlers 90° open 129.7 cm^2, 47.6% airflow airblast nozzles, 9.8 cm^2, 3.6% airflow

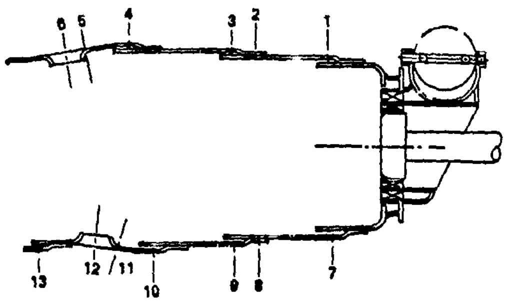

Figure A-6. Combustor Orifice Pattern, Concept 2, Engine Test No. 4.

OUTER LINER

ROW NUMBER	TYPE OF ORIFICE	NUMBER OF ORIFICES	DIAMETER, cm	GEOMETRIC AREA, cm^2	AIRFLOW, PERCENT OF INLET CONFIGURATION			
					A	B	C	D
1	Cooling	180	0.267	6.7	6.0	2.95	2.7	2.5
2	Primary	40	0.635	12.7	7.9	3.75	3.5	3.2
3	Cooling	180	0.206	6.0	3.4	1.55	1.4	1.3
4	Cooling	180	0.16	3.6	2.0	0.9	0.8	0.7
5	Dilution	40	0.89	24.8	10.4	5.3	5.0	4.1
6	Dilution	40	0.932	27.3	15.9	7.9	7.45	7.6

INNER LINER

ROW NUMBER	TYPE OF ORIFICE	NUMBER OF ORIFICES	DIAMETER, cm	GEOMETRIC AREA, cm^2	AIRFLOW, PERCENT OF INLET CONFIGURATION			
					A	B	C	D
7	Cooling	120	0.267	6.7	3.4	2.0	1.9	1.75
8	Primary	40	0.635	12.7	7.3	4.1	3.9	3.7
9	Cooling	120	0.206	4.0	2.2	1.2	1.1	1.0
10	Cooling	120	0.16	2.4	1.3	0.7	0.7	0.6
11	Dilution	40	0.89	24.8	10.2	5.9	5.6	5.0
12	Dilution	40	0.932	27.3	16.2	9.4	8.9	8.7
13	Cooling	120	0.16	2.4	1.35	0.8	0.75	0.7

A 3551852-2 swirlers closed 13.3 cm^2, 6.2% airflow, airblast nozzles, 9.8 cm^2, 4.9% airflow

B 3551852-2 30° open, 146.6 cm^2, 49.0% airflow, airblast nozzles, 9.8 cm^2, 3.3% airflow

C 3551852-2 60° open, 160.4 cm^2 51.9% airflow, airblast nozzles, 9.8 cm^2, 3.2% airflow

D 3551852-2 90° open, 188.3 cm^2, 54.8% airflow, airblast nozzles, 9.8 cm^2, 3.1% airflow

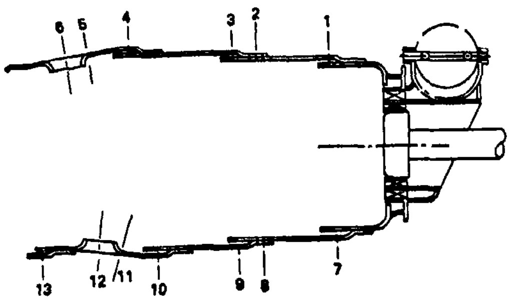

Figure A-7. Combustor Orifice Pattern, Concept 2, Engine Test No. 5.

OUTER LINER

ROW NUMBER	TYPE OF ORIFICE	NUMBER OF ORIFICES	DIAMETER, cm	GEOMETRIC AREA, cm^2	AIRFLOW, PERCENT OF INLET CONFIGURATION A
1	Cooling	120	0.267	6.7	3.2
2	Primary	40	0.635	12.7	6.3
3	Cooling	180	0.206	6.0	2.7
4	Cooling	180	0.16	3.6	1.6
5	Dilution	40	1.39	60.9	20.1
6	Dilution	40	1.13	40.1	11.8

INNER LINER

ROW NUMBER	TYPE OF ORIFICE	NUMBER OF ORIFICES	DIAMETER, cm	GEOMETRIC AREA, cm^2	AIRFLOW, PERCENT OF INLET CONFIGURATION A
7	Cooling	120	0.267	6.7	2.5
8	Primary	4υ	0.635	12.7	5.5
9	Cooling	120	0.206	4.0	1.6
10	Cooling	120	0.16	2.4	1.0
11	Dilution	40	1.13	40.1	12.4
12	Dilution	40	1.39	60.9	19.6
13	Cooling	120	0.16	2.4	1.0

A 3551852-2 swirlers closed, 13.3 cm^2, 7.9% airflow, airblast nozzles; 9.8 cm^2, 4.1% airflow

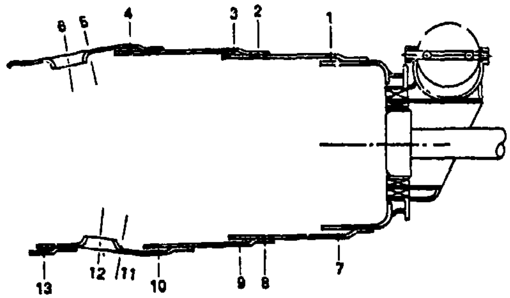

Figure A-8. Combustor Orifice Pattern, Concept 2, Engine Test No. 6.

OUTER LINER

ROW NUMBER	TYPE OF ORIFICE	NUMBER OF ORIFICES	DIAMETER, cm	GEOMETRIC AREA, cm^2	AIRFLOW, PERCENT OF INLET CONFIGURATION A
1	Cooling	120	0.267	6.7	4.7
2	Primary	40	0.3175	3.2	2.35
3	Cooling	180	0.206	6.0	4.15
4	Cooling	180	0.16	3.6	2.5
5	Dilution	40	0.85	22.75	10.7
6	Dilution	40	1.13	40.1	19.9

INNER LINER

ROW NUMBER	TYPE OF ORIFICE	NUMBER OF ORIFICES	DIAMETER, cm	GEOMETRIC AREA, cm^2	AIRFLOW, PERCENT OF INLET CONFIGURATION A
7	Cooling	120	0.267	6.7	4.2
8	Primary	40	0.3175	3.2	2.2
9	Cooling	120	0.206	4.0	2.6
10	Cooling	120	0.16	2.4	1.6
11	Dilution	40	0.81	20.7	9.9
12	Dilution	40	1.13	40.1	19.5
13	Cooling	120	0.16	2.4	1.6

A 3551852-2 swirlers closed, 13.3 cm^2, 7.15% airflow airblast nozzles 9.8 cm^2, 5.6% airflow

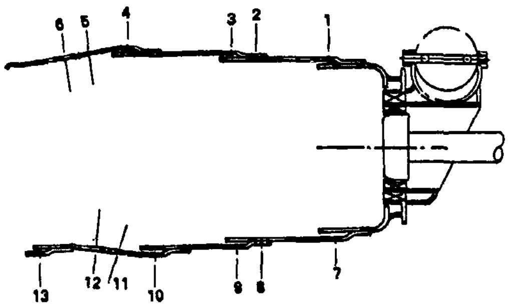

Figure A-9. Combustor Orifice Pattern, Concept 2, Engine Test No. 7.

OUTER LINER

ROW NUMBER	TYPE OF ORIFICE	NUMBER OF ORIFICES	DIAMETER, cm	GEOMETRIC AREA, cm^2	AIRFLOW, PERCENT OF INLET CONFIGURATION	
					A	B
1	Cooling	120	0.267	6.7	4.8	1.9
2	Primary	20	0.3175	1.6	1.2	0.5
3	Cooling	180	0.206	6.0	4.3	1.6
4	Cooling	180	0.16	3.6	2.6	0.9
5	Dilution	40	1.13	40.1	20.4	8.5
6	Dilution	40	0.85	22.75	11.0	4.0

INNER LINER

ROW NUMBER	TYPE OF ORIFICE	NUMBER OF ORIFICES	DIAMETER, cm	GEOMETRIC AREA, cm^2	AIRFLOW, PERCENT OF INLET CONFIGURATION	
					A	B
7	Cooling	120	0.267	6.7	4.4	2.1
8	Primary	20	0.3175	1.6	1.1	0.5
9	Cooling	120	0.206	4.0	2.7	1.2
10	Cooling	120	0.16	2.4	1.6	0.7
11	Dilution	40	0.81	20.7	10.1	4.8
12	Dilution	40	1.13	40.1	19.9	9.7
13	Cooling	120	0.16	2.4	1.6	0.8

A 3551852-2 swirlers closed, 13.3 cm^2, 7.3% airflow, airblast nozzles 9.8 cm^2, 5.75% airflow

B 3551852-2 swirlers open, 174.9 cm^2, 58.35% airflow, airblast nozzle 9.8 cm^2, 3.3% airflow

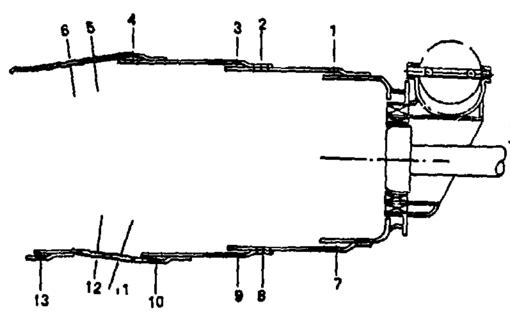

Figure A-10. Combustor Orifice Pattern, Concept 2, Engine Test No. 8.

OUTER LINER

ROW NUMBER	TYPE OF ORIFICE	NUMBER OF ORIFICES	DIAMETER, cm	GEOMETRIC AREA, cm^2	AIRFLOW, PERCENT OF INLET CONFIGURATION			
					A	B	C	D
1	Cooling	90	0.267	3.35	4.0	1.75	1.6	1.5
2	Primary	--	--	--	--	--	--	--
3	Cooling	90	0.206	3.0	2.3	1.0	0.9	0.8
4	Cooling	180	0.16	3.6	2.8	1.15	1.1	1.0
5	Dilution	40	0.71	15.9	12.45	5.5	5.15	4.8
6	Dilution	40	0.94	27.75	22.8	10.6	9.9	9.15

INNER LINER

ROW NUMBER	TYPE OF ORIFICE	NUMBER OF ORIFICES	DIAMETER, cm	GEOMETRIC AREA, cm^2	AIRFLOW, PERCENT OF INLET CONFIGURATION			
					A	B	C	D
7	Cooling	120	0.267	6.7	2.4	1.2	1.15	1.1
8	Primary	--	--	--	--	--	--	--
9	Cooling	120	0.206	4.0	1.45	0.7	0.7	0.6
10	Cooling	120	0.16	2.4	1.8	0.9	0.8	0.8
11	Dilution	40	0.81	20.7	11.05	5.6	5.3	5.0
12	Dilution	40	1.13	40.1	21.75	11.4	10.8	10.15
13	Cooling	120	0.16	2.4	1.8	1.9	0.9	0.8

A 3551852-2 swirlers closed 13.3 cm^2, 7.85% airflow, airblast nozzles 9.8 cm^2, 6.2% airflow
B 3551852-2 30° open, 146.6 cm^2, 54.3% airflow, airblast nozzles 9.8 cm^2, 3.6% airflow
C 3551852-2 60° open, 160.4 cm^2 57% airflow, airblast nozzles 9.8 cm^2, 3.5% airflow
D 3551852-2 90° open, 188.3 cm^2, 59.75% airflow, airblast nozzles 9.8 cm^2, 3.4% airflow

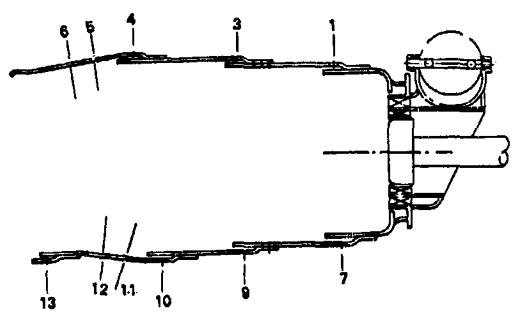

Figure A-11. Combustor Orifice Pattern, Concept 2, Engine Test No. 9.

OUTER LINER

ROW NUMBER	TYPE OF ORIFICE	NUMBER OF ORIFICES	DIAMETER cm	TOTAL AREA, cm2	AIRFLOW, PERCENT OF INLET CONFIGURATION		
					TEST 1 A	TEST 2 B	TEST 3 C
1	Cooling	180	0.204	5.91	3.0	3.2	2.9
2	Primary	80	0.298	5.60	3.0	3.3	3.0
3	Cooling	180	0.143	2.91	1.45	1.6	1.4
4	Main Stage	40	1.89	52.2	24.2	24.3	23.0
5	Cooling	300	0.154	5.56	2.4	2.6	2.3
6	Cooling	180	0.204	5.91	2.5	2.4	2.1
7	Dilution	40	0.81	41.3	-	19.6	17.5
8	Dilution	79	1.146	81.4	24.8	-	-

INNER LINER

ROW NUMBER	TYPE OF ORIFICE	NUMBER OF ORIFICES	DIAMETER cm	TOTAL AREA, cm 2	AIRFLOW, PERCENT OF INLET CONFIGURATION		
					TEST 1 A	TEST 2 B	TEST 3 C
11	Cooling	120	0.248	5.78	2.1	2.6	2.4
12	Primary	40	0.351	3.86	1.6	2.0	1.85
13	Cooling	120	0.174	2.85	1.1	1.4	1.3
14	Cooling	300	0.156	5.75	2.1	2.85	2.5
15	Cooling	120	0.235	5.20	1.9	2.6	2.4
16	Dilution	80	0.709	31.6	-	17.7	16.4
17	Cooling	120	0.204	3.94	1.4	2.1	1.9
18	Dilution	60	0.879	36.4	16.6	-	-

Swirlers: 20 Radial Inflow Part 3551448-5, Area = 17.3 cm^2, Test 1 airflow = 7.6%, Test 2 Airflow = 7.7%, Test 3 Airflow = 7.15%

Pilot Fuel Nozzles: Tests 1 and 2 Airblast Nozzles Area = 7.6 cm^2, Test 1 Airflow = 3.0%, Test 2 Airflow = 3.1%, Test 3 Pressure Atomizer Area = 23.0 cm^2, Shroud Airflow = 10.3%

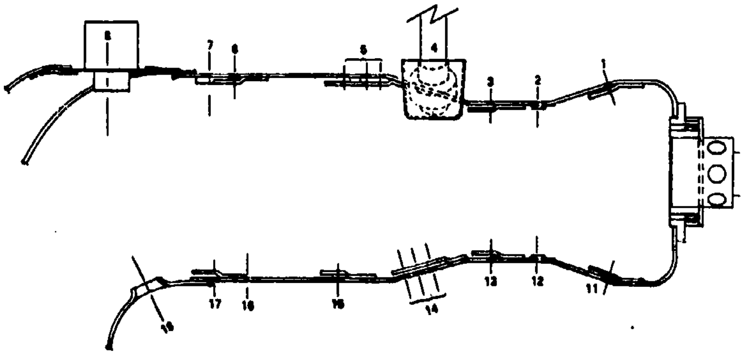

Figure A-12. Combustor Orifice Pattern, Concept 3, Tests 1, 2, and 3.

APPENDIX B

EXPERIMENTAL TEST RESULTS

ORIGINAL PAGE IS OF POOR QUALITY

Configuration--Ref. Appendix A Figure	Condition Number	Total Combustor Airflow, kg/sec	Air Assist Flow, kg/sec	Total Fuel Flow, kg/sec	Primary Fuel Flow, kg/sec	Secondary Fuel Flow, kg/sec	Inlet Total Temp, Deg K	Inlet Total Pressure, kPa	Ref. Velocity, m/sec	Temp. Spread Factor	Inlet Air Humidity, g/kg	Fuel/Air Ratio, Metered	Fuel/Air Ratio, Carbon Balance	CO_2, % by Vol. (Dry)	COEI, g/kg Fuel	HCEI, g/kg Fuel	NO_xEI, g/kg Fuel (Corr. for Humidity)	Combustion Efficiency, Gas Sample, %	Comments
CONCEPT NO. 2, RIG TEST NO. 1A (Feb 7, 1979)																			
A-1A	100	1.914	--	--	--	--	367.3	198.4	6.374	--	0.298	--	--	--	--	--	--	--	Isothermal Conditions
	190	1.929	--	--	--	--	366.6	196.9	6.462	--	0.298	--	--	--	--	--	--	--	
	200	2.344	--	--	--	--	365.9	196.4	7.971	--	0.298	--	--	--	--	--	--	--	
	290	2.333	--	--	--	--	367.7	196.8	7.946	--	0.298	--	--	--	--	--	--	--	
	300	2.727	--	--	--	--	368.1	196.0	9.481	--	0.298	--	--	--	--	--	--	--	
	390	2.726	--	--	--	--	368.3	196.3	9.470	--	0.298	--	--	--	--	--	--	--	
	2000	2.290	--	0.0242	0.0242	--	369.0	202.8	7.569	0.341	0.298	0.01057	0.01132	2.10	86.747	59.948	1.830	92.701	Taxi-Idle
	3000	5.748	--	0.0665	0.0359	0.0306	506.0	528.2	10.139	0.208	0.298	0.01157	0.01290	2.61	10.650	8.538	5.570	99.001	Approach
	3100	5.729	--	0.0654	0.0134	0.0521	506.1	531.3	10.036	0.275	0.298	0.01142	0.01261	2.55	15.301	5.615	5.268	99.148	
A-1B	3145	5.713	--	0.0654	0.0134	0.0521	505.7	531.3	10.006	0.318	0.298	0.01145	0.01239	2.47	36.484	9.884	4.498	98.275	
A-1C	4090	3.946	--	0.0616	0.0134	0.0483	647.7	413.6	11.379	0.203	0.298	0.01562	0.01677	3.39	13.711	3.346	6.627	99.384	Cruise
	5090	4.001	--	0.0589	0.0100	0.0489	668.1	413.8	11.925	0.204	0.298	0.01472	0.01602	3.25	10.783	1.666	7.079	99.600	Climbout
	6090	3.887	--	0.0608	0.0100	0.0508	683.6	414.2	11.827	0.227	0.298	0.01564	0.01713	3.48	7.336	0.751	6.595	99.762	Takeoff
	6190	3.905	--	0.0603	--	0.0603	684.4	414.3	11.901	0.228	0.298	0.01544	0.01722	3.50	7.398	0.642	6.460	99.770	Takeoff
CONCEPT NO. 2, RIG TEST NO. 1B (Feb 23, 1979)																			
A-1A	2000	2.282	--	0.0242	0.0242	--	372.0	203.0	7.530	0.360	0.149	0.01061	0.01063	1.71	119.848	181.520	1.091	81.259	Taxi-Idle
	3000	5.816	--	0.0665	0.0359	0.0306	507.3	531.2	10.054	0.174	0.149	0.01144	0.01184	2.41	7.521	6.358	5.229	99.265	Approach
	3100	5.827	--	0.0654	0.0134	0.0521	507.8	529.0	10.135	0.145	0.149	0.01123	0.01184	2.41	9.081	2.944	5.353	99.528	Approach
A-1C	4090	3.885	--	0.0623	0.0134	0.0489	643.8	413.7	10.972	0.236	0.149	0.01603	0.01592	3.22	14.663	2.037	6.700	99.476	Cruise
	5090	3.961	--	0.0591	0.0134	0.0458	665.9	411.2	11.593	0.247	0.149	0.01492	0.01486	3.01	14.467	2.535	7.002	99.437	Climbout
	6090	3.907	--	0.0591	0.0134	0.0458	683.0	414.7	11.687	0.231	0.149	0.01513	0.01513	3.07	11.762	1.749	7.487	99.570	Takeoff
CONCEPT NO. 2, RIG TEST NO. 2 (March 23, 1979)																			
A-1A	2000	2.103	--	0.0242	0.0242	--	371.1	203.7	6.944	0.137	0.534	0.01151	0.01113	1.90	116.846	125.511	1.304	86.242	Taxi-Idle
	3000	5.694	--	0.0665	0.0359	0.0306	506.4	496.2	10.673	0.092	0.534	0.01168	0.01248	2.54	8.749	2.492	4.967	99.576	Approach
	3100	5.755	--	0.0654	0.0134	0.0521	503.8	528.3	10.041	0.103	0.534	0.01137	0.01253	2.56	9.478	0.552	5.267	99.729	
A-1B	3145	5.757	--	0.0654	0.0134	0.0521	504.9	516.6	10.335	0.152	0.534	0.01136	0.01246	2.49	39.592	8.322	4.438	98.339	
A-1C	4090	3.796	--	0.0616	0.0134	0.0483	645.4	414.5	10.797	0.099	0.534	0.01624	0.01689	3.42	16.575	0.163	6.471	99.596	Cruise
	5090	3.847	--	0.0591	0.0134	0.0458	668.3	413.7	11.373	0.106	0.534	0.1537	0.01613	3.27	13.110	0.071	6.101	99.685	Climbout
	6090	3.780	--	0.0591	0.0134	0.0458	684.8	413.7	11.448	0.097	0.534	0.01564	0.01633	3.32	9.778	0.013	6.576	99.769	Takeoff
	6190	3.789	--	0.0594	0.0199	0.0394	684.7	414.5	11.454	0.095	0.534	0.01567	0.01629	3.31	10.182	0.030	6.507	99.758	
	6290	3.780	--	0.0598	0.0266	0.0331	685.4	414.2	11.442	0.097	0.534	0.01581	0.01641	3.33	10.068	0.025	6.506	99.761	
A-1A	2001	2.075	--	0.0242	0.0242	--	369.1	203.8	6.820	0.141	0.534	0.01166	0.01099	1.87	125.172	122.836	1.244	86.281	Taxi-Idle
	2100	2.083	--	0.0309	0.0309	--	367.1	202.3	6.851	0.114	0.534	0.01484	0.01405	2.63	88.788	46.016	1.633	93.875	Taxi, F/A = 0.015

Configuration--Ref. Appendix A Figure	Condition Number	Total Combustor Airflow, kg/sec	Air Assist Flow, kg/sec	Total Fuel Flow, kg/sec	Primary Fuel Flow, kg/sec	Secondary Fuel Flow, kg/sec	Inlet Total Temp, Deg K	Inlet Total Pressure, kPa	Ref. Velocity, m/sec	Temp. Spread Factor
CONCEPT NO. 2, RIG TEST NO. 3 (March 29, 1979)										
A-1A	2000	2.078	--	0.0242	0.0242	--	371.1	207.3	6.693	0.136
CONCEPT NO. 2, RIG TEST NO. 4 (April 19, 1979)										
A-1A	2000	2.103	--	0.0242	0.0242	--	372.1	199.6	7.062	0.168
	3000	5.702	--	0.0665	0.0353	0.0306	507.6	524.6	10.030	0.082
CONCEPT NO. 2, RIG TEST NO. 5 (April 25, 1979)										
A-2A	2000	2.144	--	0.0242	0.0242	--	371.7	195.5	7.197	0.134
	2100	1.744	--	0.0242	0.0242	--	374.4	199.7	5.838	0.090
	2200	1.517	--	0.0242	0.0242	--	372.5	200.7	5.004	0.080
A-2B	5090	3.901	--	0.0591	0.0134	0.0458	655.9	407.0	11.448	0.055
CONCEPT NO. 2, RIG TEST NO. 6 (May 2, 1979)										
A-3A	2200	2.223	--	0.0346	0.0346	--	376.0	203.8	7.385	0.067
	2300	1.841	--	0.0242	0.0242	--	375.4	198.8	6.217	0.064
	2400	1.608	--	0.0242	0.0242	--	372.8	201.5	5.292	0.074
CONCEPT NO. 2, RIG TEST NO. 7 (May 16, 1979)										
A-4A	2000	2.227	--	0.0242	0.0242	--	372.1	199.1	7.473	0.107
	2100	2.227	--	0.0300	0.0300	--	373.3	198.2	7.529	0.115
	3000	5.620	--	0.0665	0.0359	0.0306	504.4	519.8	9.163	0.097
A-4E	5090	3.943	--	0.0591	0.0134	0.0458	665.1	403.1	11.813	0.084
	6090	3.862	--	0.0604	0.0134	0.0470	679.6	406.2	11.715	0.092
CONCEPT NO. 2, RIG TEST NO. 8 (August 10, 1979)										
A-5A	2000	2.470	--	0.0242	0.0242	--	373.9	202.1	7.477	0.226

Configuration--Ref. Appendix A Figure	Condition Number	Inlet Air Humidity, g/kg	Fuel/Air Ratio, Metered	Fuel/Air Ratio, Carbon Balance	CO_2 % by Vol. (Dry)	COEI, g/kg Fuel	HCEI, g/kg Fuel	NO_xEI, g/kg Fuel (Corr. for Humidity)	Combustion Efficiency, Gas Sample, %	Comments
CONCEPT NO. 2, RIG TEST NO. 3 (March 29, 1979)										
A-1A	2000	0.547	0.01165	0.01072	1.95	107.529	68.410	0.886	91.470	Taxi-Idle
CONCEPT NO. 2, RIG TEST NO. 4 (April 19, 1979)										
A-1A	2000	0.429	0.01151	0.01140	1.76	152.830	194.742	0.917	79.332	Taxi-Idle
	3000	0.429	0.01166	0.01227	2.49	6.114	7.107	4.102	99.233	Approach Scoops Added
CONCEPT NO. 2, RIG TEST NO. 5 (April 25, 1979)										
A-2A	2000	0.137	0.01129	0.01132	2.00	114.890	94.317	1.240	85.024	Taxi-Idle
	2100	0.137	0.01398	0.01322	2.58	45.447	24.411	1.737	96.696	Taxi F/A = 0.013
	2200	0.137	0.01596	0.01492	2.99	27.088	7.372	2.330	98.716	Taxi F/A = 0.015
A-2B	5090	0.137	0.01515	0.01579	3.28	12.725	0.587	5.835	99.649	Climbout
CONCEPT NO. 2, RIG TEST NO. 6 (May 2, 1979)										
A-3A	2200	0.435	0.01556	0.01515	3.06	18.944	2.108	2.787	99.369	
	2300	0.435	0.01315	0.01323	2.68	19.074	3.513	2.721	99.243	
	2400	0.435	0.01506	0.01472	2.99	13.264	1.685	2.881	99.540	
CONCEPT NO. 2, RIG TEST NO. 7 (May 16, 1979)										
A-4A	2000	0.348	0.01087	0.01087	2.15	40.465	18.245	2.338	97.448	Taxi-Idle
	2100	0.348	0.01347	0.01322	2.65	25.279	8.624	2.679	98.649	Taxi-Idle
	3000	0.348	0.01183	0.01210	2.47	4.684	0.611	5.328	99.836	Approach
A-4E	5090	0.348	0.01457	0.01461	2.97	7.829	0.461	6.713	99.775	Climbout
	6090	0.348	0.01563	0.01507	3.07	5.499	0.168	7.388	99.856	Takeoff
CONCEPT NO. 2, RIG TEST NO. 8 (August 10, 1979)										
A-5A	2000	0.435	0.01066	0.01023	2.07	21.878	3.262	2.779	99.199	Taxi-Idle

CONCEPT NO. 3, RIG TEST NO. 1
(Feb. 20, 1980)

Configuration--Ref. Appendix A Figure	Condition Number	Total Combustor Airflow, kg/sec	Air Assist Flow, kg/sec	Total Fuel Flow, kg/sec	Primary Fuel Flow, kg/sec	Secondary Fuel Flow, kg/sec	Inlet Total Temp, Deg K	Inlet Total Pressure, kPa	Ref. Velocity, m/sec	Temp. Spread Factor	Inlet Air Humidity, g/kg	Fuel/Air Ratio, Metered	Fuel/Air Ratio, Carbon Balance	CO_2, % by Vol. (Dry)	COEI, g/kg Fuel	HCEI, g/kg Fuel	NO_x EI g/kg Fuel (Corr. for Hum.)	Combustion Efficiency, Gas Sample, %	NOTE	Comments
A-12A	1401	3.953	--	0.0185	0.0185	--	684.5	417.3	12.912	0.141	0.373	0.00468	0.00481	0.99	1.766	0.578	8.822	99.968	1	Takeoff
	1402	3.940	--	0.0153	0.0153	--	687.0	417.5	12.916	0.145	0.373	0.00389	0.00403	0.83	2.586	0.486	8.084	99.897	1	
	1403	3.950	--	0.0221	0.0221	--	686.7	417.8	12.934	0.114	0.373	0.00560	0.00575	1.19	1.482	0.206	10.226	99.947	1	
	1405	3.952	--	0.0601	0.0180	0.0421	687.4	420.2	11.621	0.307	0.174	0.01521	0.01516	3.09	3.633	0.295	8.403	99.889	2	
	1407	3.923	--	0.0608	0.0123	0.0485	689.0	419.4	11.591	0.388	0.174	0.01549	0.01537	3.13	6.816	0.890	9.308	99.762	3	
	1415	3.932	0.00524	0.0608	0.0180	0.0428	687.4	420.5	11.560	0.303	0.174	0.01546	0.01522	3.10	3.675	0.664	8.109	99.855	4	
	1435	3.917	0.00515	0.0614	0.0181	0.0433	685.5	421.4	11.459	0.372	0.174	0.01567	0.01529	3.11	6.001	0.889	7.719	99.781	5	
	1455	3.900	0.00514	0.0617	0.0180	0.0438	686.1	421.6	11.406	0.403	0.174	0.01583	0.01543	3.15	4.211	0.345	7.501	99.871	6	
	1454	3.976	0.00685	0.0609	0.0238	0.0371	687.1	408.8	12.048	0.321	0.174	0.01532	0.01502	3.07	2.859	0.055	7.363	99.928	7	Climb-out
	1355	4.013	--	0.0587	0.0179	0.0408	669.0	403.3	11.745	0.330	0.193	0.01464	0.01415	2.87	15.759	1.530	6.849	99.495	8	
	1305	3.979	--	0.0585	0.0177	0.0409	669.3	403.9	11.632	0.284	0.193	0.01473	0.01430	2.90	12.559	1.001	7.892	99.617	9	Approach
	1201	5.737	--	0.0670	0.0568	0.0102	505.6	538.0	9.779	0.197	0.155	0.01168	0.01158	2.30	52.595	4.250	6.015	98.390	10	
	1202	5.747	--	0.0668	0.0617	0.0050	505.8	537.2	9.816	0.165	0.168	0.01162	0.01163	2.34	32.060	2.196	6.579	99.053	11	
	1222	5.734	--	0.0667	0.0617	0.0050	505.4	538.4	9.762	0.199	0.168	0.01164	0.01161	2.33	36.729	2.557	6.526	98.912	12	
	1203	5.706	--	0.0670	0.0636	0.0034	507.1	542.7	9.662	0.223	0.168	0.01175	0.01199	2.43	24.179	1.248	6.630	99.322	13	
	1204	5.743	--	0.0668	0.0662	0.0006	497.5	539.0	9.613	0.224	0.168	0.01163	0.01190	2.43	9.140	0.198	7.218	99.768	14	Taxi-Idle
	1121	2.344	0.01657	0.0196	0.0196	--	369.3	202.9	8.329	0.184	0.730	0.00836	0.00866	1.76	25.697	3.111	2.596	99.123	15	
	1141	2.340	0.02546	0.0198	0.0198	--	368.8	203.1	8.291	0.227	0.730	0.00848	0.00599	1.21	32.420	2.090	3.768	99.054	16	
	1161	2.357	0.03444	0.0198	0.0198	--	368.2	203.5	8.321	0.230	0.730	0.00838	0.00881	1.80	8.845	0.736	2.603	99.727	17	
	1102	2.325	0.00574	0.0246	0.0246	--	369.0	202.9	8.258	0.231	0.730	0.01060	0.01009	2.02	48.643	2.128	2.806	98.669	18	
	1122	2.344	0.01634	0.0246	0.0246	--	369.1	203.5	8.291	0.192	0.730	0.01051	0.01038	2.11	21.942	1.610	3.187	99.343	15	
	1142	2.348	0.02557	0.0247	0.0247	--	369.3	203.5	8.309	0.186	0.730	0.01050	0.01046	2.13	16.833	0.517	3.053	99.559	16	
	1162	2.355	0.03595	0.0246	0.0246	--	369.4	203.6	8.328	0.191	0.730	0.01045	0.01031	2.11	11.659	0.447	3.109	99.687	17	

NOTE:
15 138 kPa air assist or pilot nozzles
16 275.8 kPa air assist or pilot nozzles
17 413.7 kPa air assist or pilot nozzles
18 No air assist

NOTE:
1 Pilot only
2 70% main fuel flow
3 80% main fuel flow
4 70% main fuel flow, 48 kPa air assist on main nozzles
5 70% main fuel flow, 180.6 kPa air assist on main nozzles
6 70% main fuel flow, 359.2 kPa air assist on main nozzles
7 60% main fuel flow, 367.4 kPa air assist on main nozzles
8 70% main fuel flow, 363.4 kPa air assist on main nozzles
9 70.1% main fuel flow
10 15% main fuel flow
11 7.4% main fuel flow
12 7.4% main fuel flow, 160.6 kPa air assist on main nozzles
13 5% main fuel flow
14 1% main fuel flow

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CONCEPT NO. 3, RIG TEST NO. 2
(March 27, 1980)

Configuration--Ref. Appendix A Figure	Condition Number	Total Combustor Airflow, kg/sec	Air-Assist Flow, kg/sec	Total Fuel Flow, kg/sec	Primary Fuel Flow, kg/sec	Secondary Fuel Flow, kg/sec	Inlet Total Temp, Deg K	Inlet Total Pressure, kPa	Ref. Velocity, m/sec	Temp. Spread Factor	Inlet Air Humidity, g/kg	Fuel/Air Ratio, Metered	Fuel/Air Ratio, Carbon Balance	CO_2, Percent By Volume (Dry)	CO Emission Index, g/kg	HC Emission Index, g/kg	NO_x Emission Index, Corr. For Humidity, g/kg	Combustion Efficiency, Gas Sample.
A-12B	2122	2.294	0.01597	0.0243	0.0243	--	370.8	203.0	7.497	0.183	0.193	0.01060	0.01092	2.21	23.324	1.429	3.072	99.3261
	2403	3.914	--	0.0218	0.0218	--	682.1	416.5	11.528	0.372	0.137	0.00557	0.00646	1.32	14.235	7.204	8.241	99.0332
	2407	3.955	--	0.0616	0.0123	0.0493	684.7	416.9	11.680	0.176	0.137	0.01558	0.01622	3.24	36.073	5.675	5.984	99.6543
	2404	3.937	--	0.0606	0.243	0.0364	683.4	416.7	11.611	0.156	0.137	0.01540	0.01660	3.35	18.748	3.421	6.428	99.2594
	2408	3.937	--	0.0610	0.0306	0.0304	685.5	417.5	11.625	0.143	0.137	0.01548	0.01675	3.39	11.270	1.343	7.121	99.6175

NOTE:
1 14.1 kPa air assist pressure on pilot nozzles
2 Pilot only
3 80% main fuel flow
4 60% main fuel flow
5 50% main fuel flow

CONCEPT NO. 3, RIG TEST NO. 3

Configuration--Ref. Appendix A Figure	Condition Number	Total Combustor Airflow, kg/sec	Air Assist Flow, kg/sec	Total Fuel Flow, kg/sec	Primary Fuel Flow, kg/sec	Secondary Fuel Flow, kg/sec	Inlet Total Temp, Deg K	Inlet Total Pressure, kPa	Ref. Velocity, m/sec	Temp. Spread Factor	Inlet Air Humidity, g/kg	Fuel/Air Ratio, Metered	Fuel/Air Ratio, Carbon Balance	CO_2, % by Vol. (Dry)	COEI, g/kg Fuel	HCEI, g/kg Fuel	NOx EI g/kg Fuel (Corr. for Hum.)	Combustion Efficiency, Gas Sample, %	SAE Smoke Number	NOTE	Comments
(May 1, 1980)																					
A-12C	3101	2.233	--	0.0193	0.0193	--	370.4	202.2	7.324	0.173	0.205	0.00863	0.00937	1.88	34.163	6.168	3.020	98.655			Taxi-Idle
	3102	2.262	--	0.0244	0.0244	--	371.0	202.4	7.428	0.162	0.478	0.01079	0.01142	2.31	25.251	1.466	3.415	99.277			↓
	3103	2.273	--	0.0292	0.0292	--	369.8	203.4	7.405	0.147	0.466	0.01284	0.01329	2.69	23.663	0.418	3.335	99.407			
	3403	3.889	--	0.0243	0.0243	--	683.4	415.2	11.491	0.129	0.391	0.00625	0.00713	1.47	2.379	0.187	8.991	99.928		1	Takeoff
	3404	3.900	--	0.0609	0.0244	0.0365	686.4	417.1	11.530	0.108	0.391	0.01562	0.01608	3.28	1.729	0.141	6.321	99.947		2	↓
	3454	3.917	0.01932	0.0607	0.0244	0.0364	682.8	417.2	11.514	0.112	0.354	0.01551	0.01609	3.28	1.495	0.040	5.314	99.961		3	
	3457	3.916	0.01933	0.0613	0.0124	0.0489	683.9	416.8	11.541	0.155	0.311	0.01566	0.01641	3.34	5.672	0.194	5.098	99.850		4	
	3407	3.886	0.00348	0.0612	0.0123	0.0489	685.5	417.6	11.460	0.167	0.311	0.01574	0.01639	3.33	7.403	0.291	6.041	99.800		5	
	3357	3.988	0.01936	0.0591	0.0118	0.473	666.0	416.2	11.466	0.170	0.311	0.01482	0.01545	3.13	16.289	1.447	4.095	99.490		6	Climbout
	3354	3.977	0.01933	0.0589	0.0238	0.035[illegible]	666.0	420.4	11.316	0.110	0.311	0.01481	0.01540	3.14	2.760	0.000	4.661	99.935		7	↓
	3355	3.982	0.01941	0.0590	0.0178	0.0412	664.7	420.2	11.314	0.135	0.311	0.01482	0.01546	3.15	6.780	0.187	4.650	99.824		8	
(May 22, 1980)																					
	3307	4.005	--	0.0592	0.0117	0.0475	661.8	415.0	11.482	0.230	0.162	0.01477	0.01512	3.05	20.710	2.307	6.693	99.310	13	9	Climbout
	3304	3.954	--	0.0550	0.0236	0.0354	663.2	416.7	11.301	0.127	0.162	0.01491	0.01526	3.11	3.519	0.155	6.982	99.904	9.5	10	↓
	3204	5.612	--	0.0662	0.0595	0.0067	502.4	534.2	9.454	0.117	0.124	0.01179	0.01250	2.47	54.798	9.005	5.916	97.921	14	11	Approach
	3203	5.712	--	0.0661	0.0629	0.0033	502.8	538.0	9.580	0.151	0.143	0.01158	0.01226	2.45	40.330	4.837	6.044	98.627		12	↓
	3205	5.689	--	0.0663	0.0656	0.0007	503.4	537.9	9.552	0.187	0.143	0.01165	0.01221	2.49	11.520	0.715	6.618	99.666		13	
	3206	5.743	--	0.0662	0.0662	--	502.9	537.6	9.642	0.177	0.143	0.01152	0.01216	2.49	5.451	0.276	6.758	99.848		14	

NOTE:
1 Pilot only
2 60% main fuel flow
3 60% main fuel flow, 345 kPa air assist on main nozzles
4 79.8% main fuel flow, 345 kPa air assist on main nozzles
5 79.9% main fuel flow, no air assist
6 80.0% main fuel flow, 346 kPa air assist on main nozzles
7 50% main fuel flow, 393 kPa air assist on main nozzles
8 69.9% main fuel flow, 343 kPa air assist on main nozzles
9 80.2% main fuel flow, no air assist
10 60%, main fuel flow, no air assist
11 10% main fuel flow, no air assist
12 5% main fuel flow
13 1% main fuel flow
14 Pilot only

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Configuration	Engine Test No.	Condition Number	Total Combustor Airflow, kg/sec	Total Fuel Flow, kg/sec	Thrust (Corrected) kN	Combustor Inlet Temperature, K	Combustor Inlet Total Pressure, kPa	Engine Inlet Temperature, K	Engine Inlet Pressure, kPa	Inlet Air Humidity, g/g	Fuel-Air Ratio (Metered)	Fuel-Air Ratio (Carbon Bal.)	CO_2 % by Vol. (Dry)	COEI, g/kg Fuel	HCEI, g/kg Fuel	NO_x EI, g/kg Fuel (Corr. for Humidity)	Combustion Efficiency, Gas Sample	SAE Smoke Number	Comments
					TFE731-2, Serial No. 7353, Engine Test 1, July 9, 1979														
A-4A	1	2000	2.32	0.0272	0.91	410.2	195.8	317.0	96.9	0.00327	0.0132	0.0121	2.49	30.1	5.38	3.15	98.8	--	Idle
		3000	5.20	0.0620	3.18	521.6	413.0	317.6	96.9		0.0134	0.0135	2.83	3.9	0.13	6.63	99.9	--	Rich-Idle
A-4B		3022	5.23	0.1365	3.19	521.7	410.2	317.8	96.9		0.0133	0.0134	2.81	6.3	0.13	5.69	99.8	--	
A-4C		3045	5.36	0.0616	3.23	520.4	406.0	317.4	96.9		0.0230	0.0132	2.75	20.1	1.79	4.65	99.4	--	
A-4D		3067	5.38	0.0614	3.22	518.8	406.1	317.8	96.9		0.0129	0.0131	2.72	21.6	1.39	4.51	99.4	--	
A-4E		3090	5.40	0.0615	3.24	518.2	404.7	317.3	96.9		0.0128	0.0131	2.71	28.0	2.03	4.52	99.2	--	
		4090	9.01	0.1222	7.41	643.4	788.1	318.8	96.8		0.0152	0.0152	3.21	1.2	0.12	5.79	99.96	--	Sub-Approach
					July 23, 1979														
A-4A	1	2000	2.70	0.0287	0.95	400.8	198.6	308.2	96.9	0.01158	0.0118	0.0126	2.44	74.01	43.65	2.09	94.43	--	Idle
A-4E		6090	13.07	0.1812	11.38	695.4	1126.6	308.5	96.9		0.0154	0.0156	3.28	1.71	0.30	10.82	99.93	--	Rich-Approach
		5090	12.60	0.1616	10.20	676.9	1013.5	308.5	96.9		0.0142	0.0152	3.21	2.00	0.23	9.59	99.93	--	Approach
		4090	10.64	0.1340	8.48	645.5	863.2	308.9	96.9		0.0140	0.0146	3.06	3.72	0.24	8.13	99.89	--	Sub-Approach
		4190	8.43	0.0969	5.80	580.4	624.0	309.4	96.9		0.0128	0.0139	2.90	13.72	0.68	5.79	99.62	--	
		3090	5.89	0.0621	3.41	513.6	419.2	309.4	96.9		0.0117	0.0125	2.54	44.02	8.94	3.95	98.18	--	Rich-Idle
A-4A		3000	5.57	0.0626	3.37	517.1	428.2	310.2	96.9		0.0125	0.0128	2.67	10.01	1.07	5.39	99.67	--	
A-4B		3030	5.83	0.0633	3.38	517.9	426.8	311.0	96.9		0.0121	0.0129	2.64	33.03	7.85	4.27	98.54	--	
A-4C		3060	5.90	0.0629	3.39	516.9	422.6	311.0	96.9		0.0119	0.0127	2.59	44.41	8.90	3.87	98.18	--	
A-4A		2000	2.85	0.0277	9.76	406.8	202.7	310.7	96.9		0.0108	0.0115	2.25	68.63	39.31	2.20	94.94	--	Idle
					TFE731-2, Serial No. 7353, Engine Test 2, September 7, 1979														
A-5A	2	2001	2.34	0.0278	0.89	401.8	200.6	308.0	97.1	0.01048	0.0119	0.0119	2.46	22.23	5.10	3.20	99.83	5.0	Idle
		2002	2.38	0.0279	0.89	401.9	200.6	308.0	97.0		0.0117	0.0119	2.45	23.00	5.32	3.10	98.99	5.0	
		1003	2.08	0.0236	0.65	383.5	174.4	308.2	97.1		0.0114	0.0119	2.42	41.34	17.83	2.59	97.46	--	Sub-Idle
		3003	3.56	0.0418	1.82	457.7	299.2	309.0	97.1		0.0118	0.0119	2.49	5.45	0.42	4.26	99.84	--	Rich-Idle
		4003	4.23	0.0523	2.52	488.5	363.4	308.8	97.1		0.0124	0.0124	2.60	3.71	0.32	4.71	99.88	--	Sub-Approach
		5001	5.04	0.0657	3.39	520.7	446.4	309.2	97.0		0.0130	0.0130	2.73	2.81	0.21	5.64	99.92	5.0	Approach
		5002	5.04	0.0657	3.37	520.9	446.1	309.2	97.0		0.0130	0.0131	2.74	2.69	0.27	5.79	99.91	5.5	
A-5B		5032	5.06	0.0655	3.42	520.2	444.7	309.0	97.0		0.0129	0.0129	2.69	10.68	0.61	5.24	99.70	--	
		5031	5.05	0.0655	3.43	520.3	444.0	309.1	97.0		0.0130	0.0129	2.69	10.11	0.46	5.28	99.72	--	
A-5C		5061	5.15	0.0653	3.44	519.9	440.6	308.8	97.0		0.0127	0.0127	2.65	14.51	1.08	4.48	99.56	--	
		5062	5.14	0.0652	3.44	519.4	439.9	309.0	97.0		0.0127	0.0125	2.61	14.32	1.04	4.48	99.57	--	
A-5D		5092	5.21	0.0656	3.48	519.0	440.6	309.0	97.0		0.0126	0.0125	2.59	23.19	2.18	4.16	99.26	13.0	
		5091	5.16	0.0654	3.45	519.4	439.9	309.0	97.0		0.0127	0.0127	2.64	21.82	1.91	4.25	99.32	15.0	
		6093	7.03	0.0963	5.66	581.9	631.6	308.7	97.0		0.0137	0.0136	2.85	9.15	0.46	5.94	99.74	20.5	Rich-Approach
		7093	8.77	0.1289	7.95	631.4	826.7	308.7	97.0		0.0147	0.0146	3.06	3.41	0.21	7.60	99.90	23.0	Sub-Climbout
		8091	10.80	0.1641	10.29	673.7	1025.3	308.9	97.0		--	0.0152	3.20	1.50	0.16	9.48	99.95	24.0	Climbout
	2	8092	10.35	0.1645	10.32	674.3	1025.9	309.0	97.0	0.01040	0.0159	0.0152	3.20	24.0	0.16	9.72	99.95	23.0	Climbout
		9092	11.42	0.1792	11.25	690.0	1101.8	309.3	97.0		--	0.0157	3.31	19.3	0.09	10.68	99.96	23.5	Takeoff
		9091	11.12	0.1801	11.37	690.5	1105.9	309.2	97.0		0.0162	0.0156	3.28	19.4	0.11	10.73	99.96	24.5	Takeoff

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Configuration	Engine Test No.	Condition Number	Total Combustor Airflow, kg/sec	Total Fuel Flow, kg/sec	Primary Fuel Flow, kg/sec	Secondary Fuel Flow, kg/sec	Thrust (Corrected) kN	Combustor Inlet Temperature, K	Combustor Inlet Total Pressure, kPa	Engine Inlet Temperature, K	Engine Inlet Pressure, kPa	Inlet Air Humidity, g/g	Fuel-Air Ratio (Metered)	Fuel-Air Ratio (Carbon Bal.)	CO_2 % by Vol. (Dry)	COEI, g/kg Fuel	HCEI, g/kg Fuel	NO_x EI, g/kg Fuel (Corr. for Humidity)	Combustion Efficiency, Gas Sample	SAE Smoke Number	Comments
TFE731-2, Serial No. 7353, Engine Test 3, October 17, 1979																					
A-6A	3	2001	2.39	0.0269			--	--	--	--	--	0.00491	--	0.0113	2.31	29.61	9.16	2.95	98.50	--	Idle
		2002	2.46	0.0260			--	--	--	--	--		--	0.0106	2.17	33.54	11.63	2.75	98.19	--	
		1001	1.72	0.0191			--	--	--	--	--		--	0.0113	2.26	47.16	25.81	2.44	96.63	--	Sub-Idle
		3001	3.56	0.0398			--	--	--	--	--		--	0.0111	2.31	7.66	0.92	4.10	99.74	--	Rich-Idle
		2003	2.5[illegible]	0.0269			--	--	--	--	--		--	0.0112	2.31	27.79	7.82	3.10	98.66	--	Idle
		2004	[illegible].49	0.0261			--	--	--	--	--		--	0.0105	2.14	32.40	10.41	2.94	98.33	--	
October 19, 1979																					
	3	2001	2.44	0.0271			0.95	385.2	203.4	293.9	96.5	0.009135	0.0111	0.0115	2.36	25.22	6.89	2.91	98.80	--	Idle
		2002	2.44	0.0272			0.94	384.9	202.7	293.8	96.5		0.0111	0.0115	2.37	25.68	7.26	2.95	98.76	--	
		2003	2.53	0.0262			0.96	386.0	206.8	293.7	96.5		0.0104	0.0108	2.21	29.61	9.58	2.75	98.46	--	
		1001	2.07	0.0231			0.71	367.3	176.5	293.9	96.7		0.0112	0.0126	2.32	42.83	23.61	2.39	96.92	--	Sub-Idle
		3001	3.65	0.0401			1.83	433.8	297.2	293.4	95.9		0.0110	0.0113	2.37	5.92	0.26	3.76	99.84	--	Rich-Idle
		4001	4.27	0.0489			2.37	456.3	350.3	292.8	95.7		0.0113	0.0118	2.46	4.14	0.10	4.28	99.89	--	Sub-Approach
		5001	5.92	0.0740			4.16	516.9	515.0	292.9	94.7		0.0125	0.0131	2.75	2.39	0.06	5.89	99.94	--	Approach
		6001	8.45	0.1140			7.03	588.0	770.8	292.9	93.1		0.0135	0.0143	3.01	1.50	0.07	8.95	99.96	--	Rich-Approach
		2004	2.40	0.0265			0.91	385.3	200.6	294.5	96.6		0.0111	0.0114	2.35	27.16	8.04	2.79	98.66	--	Idle
A-4D		4091	4.30	0.0473			2.34	455.7	333.7	295.2	95.8		0.0110	0.0116	2.36	45.05	6.77	3.23	98.35	--	Sub-Idle
		5091		0.0735			4.22	518.4	501.2	295.2	94.7		0.0122	0.0127	2.65	20.77	1.32	4.54	99.40	--	Approach
		6091		0.1110			6.96	584.9	739.:	295.3	93.1		0.0131	0.0138	2.88	8.10	0.26	6.35	99.79	--	Rich-Approach
		7091		0.1468			9.51	632.5	950.1	295.2	91.7		0.0138	0.0148	3.11	3.53	0.06	8.14	99.91		Sub-Climbout
		8091		0.1706			11.12	658.0	1080.4	295.5	90.9		0.0144	0.0154	3.25	2.17	0.02	9.38	99.95		Climbout
		9091		0.1927			12.56	678.0	1192.8	295.3	90.0		0.0148	0.0159	3.36	1.55	0.02	10.77	99.96		Takeoff
TFE731-2, Serial No. 7353, Engine Test 4, December 14, 1979																					
A-6A	4	2001	2.39	0.0258	0.0258	--	0.95	385.0	213.0	295.3	97.9	0.002823	0.0108	0.0113	2.27	29.58	7.92	3.24	98.61	--	Idle
		2002	2.47	0.0250	0.0250	--	0.98	387.2	217.9	295.4	97.9		0.0101	0.0106	2.12	31.28	10.23	2.96	98.37	--	
		4001	4.02	0.0449	0.0413	0.0035	2.34	455.7	358.5	295.4	97.9		0.0112	0.0115	2.35	5.54	0.91	4.92	99.79	--	Sub-Approach
		5001	5.67	0.0706	0.0444	0.0262	4.16	516.9	530.2	294.5	97.9		0.0125	0.0128	2.61	3.48	0.61	6.92	99.86	--	Approach
		6001	8.10	0.1087	0.0472	0.0614	6.95	586.7	786.0	294.2	97.9		0.0134	0.0138	2.82	2.25	0.50	10.59	99.90	--	Rich-Approach
A-6B		6091	8.22	0.1070	0.0471	0.0599	7.00	582.0	772.2	293.9	97.5		0.0130	0.0133	2.72	8.21	0.59	6.95	99.76	--	
		7091	10.19	0.1417	0.0488	0.0928	9.53	629.7	988.7	294.0	97.9		0.0139	0.0143	2.92	3.55	0.29	8.95	99.89	--	Sub-Climbout
		8091	11.35	0.1650	0.0495	0.1155	11.14	654.7	1127.3	294.0	97.9		0.0145	0.0148	3.01	2.37	0.21	10.42	99.93	--	Climbout
		9091	12.22	0.1845	0.0499	0.1346	12.45	673.7	1234.2	294.2	97.9	0.002823	0.0151	0.0153	3.12	1.78	0.20	11.78	99.94	--	Takeoff
A-6A		2101	2.46	0.0253	0.0253	--	0.95	389.7	213.0	296.0	97.9		0.0103	0.0109	2.20	29.60	7.28	3.41	98.67	--	Idle
		2102	2.57	0.0250	0.0250	--	0.96	388.5	217.2	295.6	97.9		0.0097	0.0104	2.08	37.9	12.72	2.92	97.99	--	

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Configuration	Condition Number	Total Combustor Airflow, kg/sec	Total Fuel Flow, kg/sec	Primary Fuel Flow, kg/sec	Secondary Fuel Flow, kg/sec	Thrust (Corrected) kN	Combustor Inlet Temperature, K	Combustor Inlet Total Pressure, kPa	Engine Inlet Temperature, K	Engine Inlet Pressure, kPa	Inlet Air Humidity, g/g	Fuel-Air Ratio (Metered)	Fuel-Air Ratio (Carbon Bal.)	CO_2 % by Vol. (Dry)	COEI, g/kg Fuel	HCEI, g/kg Fuel	NO_x EI, g/kg Fuel (Corr. for Humidity)	Combustion Efficiency, Gas Sample	SAE Smoke Number	Comments, Surge Valve (Open or Closed)
TFE731-2, Serial No. 7353, Engine Test 5, February 19, 1980																				
A-7A	2001	2.15	0.0253	0.0253	--	0.90	377.0	207.5	290.8	97.2	0.010477	0.0118	0.0112	2.25	35.93	3.74	3.07	98.83		Open Idle
	2002	2.22	0.0244	0.0244	--	0.91	378.3	211.7	290.5			0.0110	0.0106	2.13	35.38	6.42	2.90	98.61	19.5	Closed
	4001	4.29	0.0451	0.0407	0.0044	2.36	452.7	356.5	292.3			0.0105	0.0116	2.36	8.16	0.32	4.31	99.78		Sub-Approach
A-7B	4031	4.26	0.0451	0.0411	0.0043	2.35	451.9	353.7	292.3			0.0106	0.0115	2.32	26.99	2.19	3.78	99.17		
A-7C	4061	4.36	0.0454	0.0407	0.0046	2.36	450.8	352.3	292.0			0.0104	0.0114	2.86	37.23	6.39	3.34	98.65		
A-7D	4091	4.37	0.0462	0.0407	0.0055	2.37	450.4	353.0	292.2			0.0106	0.0116	2.78	57.59	12.00	2.90	97.59		
	5091	6.02	0.0711	0.0410	0.0300	4.13	509.2	515.0	292.0			0.0118	0.0125	2.48	42.67	10.21	4.03	98.10	27.5	Approach
A-7C	5061	5.93	0.0704	0.0410	0.0294	4.13	509.4	516.4	292.2			0.0119	0.0124	2.50	30.05	6.10	4.49	98.76		
A-7B	5031	5.85	0.0701	0.0410	0.0291	4.09	510.1	518.5	292.2			0.0120	0.0124	2.52	18.49	1.13	2.95	99.39		
A-7A	5001	5.88	0.0700	0.0408	0.0291	4.07	510.7	518.5	292.3			0.0120	0.0125	2.55	5.32	0.15	3.40	99.85	30.5	
	6001	8.27	0.1098	0.0416	0.0682	6.98	581.0	786.0	292.0			0.0133	0.0136	2.78	3.27	0.19	8.17	99.90		Rich-Approach
A-7B	6031	8.26	0.1098	0.0416	0.0679	7.00	581.5	781.9	292.2			0.0133	0.0134	2.74	7.21	0.34	6.80	99.80		
A-7C	6061	8.31	0.1098	0.0416	0.0679	7.02	579.7	774.3	292.3			0.0132	0.0135	2.73	18.53	1.42	5.47	99.42		
A-7D	6091	8.39	0.1100	0.0417	0.0683	7.05	579.4	777.0	292.3			0.0131	0.0135	2.73	23.21	2.34	5.17	99.22	36.6	
	7091	10.17	0.1453	0.0435	0.1023	9.59	624.8	992.2	291.9			0.0143	0.0143	2.90	10.46	0.60	8.64	99.71	37.2	Sub-Climbout
	8091	11.16	0.1647	0.0433	0.1213	10.99	646.3	1107.3	291.9			0.0148	0.0147	2.99	6.18	0.28	11.56	99.84	39.5	Climbout
	9091	12.33	0.1426	0.0438	0.1488	12.79	672.8	1248.6	291.8			0.0156	0.0153	3.12	3.32	0.13	10.68	99.91	44	Takeoff
A-7A	2101	2.28	0.0241	0.0241	--	0.96	384.8	214.4	292.5			0.0106	0.0101	2.02	38.25	5.47	3.54	98.62		Closed Idle
	2101	2.32	0.0245	0.0245	--	0.96	383.0	214.4	292.8			0.0106	0.0103	2.06	42.20	6.78	3.12	98.41		Open
TFE731-2, Serial No. 7353, Engine Test 6, March 28, 1980																				
A-8A	2001	2.52	0.0240	0.0240	--	0.91	372.5	206.2	286.2	97.2	0.006584	0.0095	0.0104	2.07	52.10	2.65	3.73	98.54		Open Idle
	2002	3.00	0.0303	0.0303	--	1.30	394.8	245.5	286.0			0.0101	0.0107	2.16	44.02	1.28	4.09	98.85		Open
	2003	3.37	0.0352	0.0352	--	1.62	410.9	275.1	286.2			0.0105	0.0111	2.24	33.16	0.94	4.39	99.02		Open
TFE731-2, Serial No. 7353, Engine Test 7, April 16, 1980																				
A-9A	2001	2.31	0.0754	--	--	--	--	--	--		0.00563	--	0.0110	2.21	38.69	2.38	3.46	98.88		Open Idle
	2002	2.41	0.0245	--	--	--	--	--	--			--	0.0102	2.05	35.12	3.00	3.29	98.91		Closed
	2003	2.83	0.0322	--	--	--	--	--	--			--	0.0114	2.31	23.45	0.57	4.13	99.40		Closed
	2004	3.39	0.0406	--	--	--	--	--	--			--	0.0120	2.43	19.53	0.24	4.89	99.52		Closed
	4001	4.13	0.0475	--	--	--	--	--	--			--	0.0115	2.33	14.92	0.30	5.53	99.62		Sub-Approach
	2005	2.36	0.0245	--	--	--	--	--	--			--	0.0104	2.10	38.09	2.92	3.73	98.85		Closed Idle
	2006	2.28	0.0253	--	--	--	--	--	--			--	0.0111	2.24	38.93	2.21	3.91	98.89		Open
	4002	3.88	0.0446	--	--	--	--	--	--			--	0.0115	2.33	16.82	0.38	5.52	99.57		Sub-Approach
	5001	5.65	0.0711	--	--	--	--	--	--			--	0.0126	2.58	9.46	0.38	7.84	99.75		Approach
	2007	2.75	0.0375	--	--	--	--	--	--			--	0.0118	2.39	26.00	0.43	4.68	99.35		Closed Idle
	2008	--	0.0251	--	--	--	--	--	--			--	--	2.78	29.02	1.29	3.30	99.20		Open

Configuration	Engine Test No.	Condition Number	Total Combustor Airflow, kg/sec	Total Fuel Flow, kg/sec	Primary Fuel Flow, kg/sec	Secondary Fuel Flow, kg/sec	Thrust (Corrected), kN	Combustor Inlet Temperature, K	Combustor Inlet Total Pressure, kPa	Engine Inlet Temperature, K	Engine Inlet Pressure, kPa	Inlet Air Humidity, g/g	Fuel-Air Ratio (Metered)	Fuel-Air Ratio (Carbon Balance)	CO_2, % By Volume (Dry)	COEI, g/kg Fuel	HCEI, g/kg Fuel	NO_xEI, g/kg Fuel (Corr. for Humidity)	Combustion Efficiency, Gas Sample	SAE Smoke Number	Comments, Surge Valve (Open or Closed)
TFE731-2, Serial No. 7353, Engine Test 8, May 2, 1980																					
	8	2000	2.32	0.0244	0.0244	--	0.94	382.8	214.3	292.3	97.2	0.008512	--	0.0105	2.12	36.72	3.10	3.18	98.86	12.5	Closed
		2001	2.25	0.0254	0.0254	--	0.92	382.2	209.1	292.5			--	0.0113	2.26	38.58	2.27	3.20	98.89		Open
		2002	2.35	0.0246	0.0246	--	0.96	384.8	216.0	292.3			--	0.0105	2.12	34.03	2.63	3.08	98.97		Closed
		2003	2.37	0.0249	0.0249	--	0.97	385.9	218.4	292.2			--	0.0105	2.11	33.05	2.30	2.17	99.02		Closed
		2004	2.42	0.0254	0.0254	--	1.00	386.8	221.0	292.0			--	0.0105	2.11	32.22	2.07	--	99.06		Closed
		2005	2.46	0.0259	0.0259	--	1.03	389.3	224.2	291.6			--	0.0105	2.13	31.33	1.79	2.92	99.11		Closed
		4000	3.89	0.0451	0.0376	0.0075	1.59	453.7	353.8	291.7			--	0.0116	2.37	17.58	0.20	3.79	99.57	17.2	
		5000	5.55	0.0711	0.0398	0.0313	4.16	515.5	524.6	291.7			--	0.0128	2.62	10.24	0.17	5.93	99.74		
		4090	4.04	0.0469	0.0432	0.0036	2.34	448.8	350.5	291.3			--	0.0116	2.24	76.48	24.53	2.17	96.05	13.9	
		5090	5.73	0.0715	0.0454	0.0261	4.14	509.1	514.7	290.6			--	0.0127	2.51	44.55	10.04	3.25	98.07	18.1	
		6090	8.06	0.1073	0.0478	0.0596	6.86	573.5	756.6	290.4			--	0.0135	2.73	22.35	2.23	4.87	99.28	24	
		7090	10.08	0.1441	0.0486	0.0955	9.52	622.5	984.4	290.3			--	0.0144	2.92	10.02	0.30	6.71	99.74	26.7	
		8090	10.74	0.1561	0.0486	0.1075	10.38	636.8	1055.7	289.9			--	0.0147	2.98	7.41	0.02	7.88	99.82	25.5	
		9090	11.90	0.1819	0.0496	0.1323	12.12	661.0	1200.4	289.8			--	0.0154	3.14	4.17	0.09	10.14	99.89	30.0	
TFE731-2, Serial No. 7353, Engine Test 9, May 20, 1980																					
	9	2001	2.19	0.0250	0.0250	--	0.89	386.3	205.5	297.4	97.2	0.006253	0.0115	0.0113	2.28	32.47	0.42	3.30	99.20		Open
		2002	2.64	0.0242	0.0242	--	0.91	387.3	209.9	297.0			0.0091	0.0105	2.12	27.24	0.31	3.45	99.33		Closed
		2003	2.46	0.0273	0.0273	--	1.02	395.7	219.9	297.4			0.0111	0.0116	2.33	32.22	0.31	3.45	99.22		Open
		2004	2.81	0.0258	0.0258	--	1.02	395.0	222.1	297.2			0.0092	0.0107	2.17	27.58	0.34	3.57	99.32		Closed
		2005	3.92	0.0277	0.0277	--	1.14	402.6	235.0	297.2			--	0.0110	2.22	27.70	0.26	3.60	99.33		Closed
		2006	4.06	0.0293	0.0293	--	1.14	403.2	231.6	297.4			--	0.0119	2.39	32.64	0.22	3.45	99.21		Open
		4001	2.91	0.0391	0.0320	0.0071	1.89	442.3	312.3	297.7			--	0.0116	2.36	23.51	0.15	4.49	99.43		
		5001	--	0.0466	0.0329	0.0136	2.37	463.8	359.8	298.3			--	0.0122	2.46	21.11	0.18	4.94	99.49		
		6001	5.61	0.0728	--	--	4.18	524.0	530.1	297.9			0.0130	0.0132	2.69	13.84	0.19	6.64	99.66		
		4002	3.57	0.0387	--	--	1.84	440.8	308.4	297.9			0.0108	0.0116	2.34	22.69	0.25	4.47	99.45		
		4091	3.55	0.0423	--	--	1.84	441.5	302.3	301.1			0.0119	0.0126	2.26	108.20	78.02	2.18	90.61	13.0	
		2009	2.27	0.0247	--	--	0.90	398.2	210.1	305.7			0.0109	0.0107	2.15	28.09	1.18	4.03	99.24		Closed
		2010	2.17	0.0259	--	--	0.91	398.4	207.7	305.6			0.0119	0.0125	2.31	32.68	1.14	3.87	99.13		Open
		4009	3.24	0.0372	--	--	1.69	445.4	292.5	306.5			0.0115	0.0115	2.33	22.05	0.94	5.20	99.40	16.2	
		4031	3.11	0.0362	--	--	1.54	437.1	275.9	306.3			0.0116	0.0116	2.24	66.63	32.12	3.37	95.62		
		4061	3.20	0.0363	--	--	1.55	436.3	274.7	307.3			0.0115	0.0115	2.20	67.40	42.25	2.80	94.71		
		5061	4.13	0.0484	--	--	2.38	473.4	354.1	306.3			0.0117	0.0120	2.33	55.65	30.11	3.87	96.05		
		5091	4.10	0.0488	--	--	2.38	474.0	352.8	307.3			0.0119	0.0120	2.30	70.30	36.26	3.36	95.17		
		5031	4.05	0.0478	--	--	2.36	476.6	354.4	307.8			0.0118	0.0120	2.37	48.79	17.25	4.52	97.34		
		6031	--	--	--	--	4.26	542.5	529.1	307.2			--	0.0129	2.60	24.41	4.86	6.84	99.30		
A-11	C	6061	--	--	--	--	4.29	540.3	526.7	307.0	97.2	0.006253	--	0.129	2.58	37.57	8.32	6.30	98.39		Rich-Approach
A-11	D	6091	--	--	--	--	4.29	539.4	527.9	307.2			--	0.0129	2.56	55.03	10.25	5.47	97.81	19	
		7091	9.45	0.1393	0.0440	0.0953	8.90	644.9	936.4	306.6			0.0147	0.0143	2.91	7.52	0.46	10.92	99.78		Sub-Climbout
		8091	10.37	0.1582	0.0443	0.1138	10.17	668.0	1048.8	306.9			0.0152	0.0149	3.03	4.02	0.36	12.77	99.87	20	Climbout
		9091	11.46	0.1852	0.0446	0.1406	11.92	694.1	1192.6	306.5			0.0162	0.0155	3.17	1.97	0.34	15.84	99.92	22.5	Takeoff
A-11A		2011	2.33	0.0246	0.0246	--	0.90	402.1	210.7	308.0			0.0106	0.0108	2.19	30.27	1.48	4.19	99.16	8.5	Closed Idle
		4006	3.93	0.0450	--	--	2.28	456.7	350.5	295.8	96.5		0.0115	0.0116	2.35	20.87	0.42	5.34	99.47		Sub-Approach
		4007	3.91	0.0437	--	--	2.18	452.8	343.2	295.9			0.0112	0.0115	2.33	21.22	0.40	5.30	99.47		
		2013	2.31	0.0239	0.0239	--	0.90	384.3	209.2	295.5			0.0103	0.0105	2.12	25.70	0.47	3.80	99.35		Closed Idle

TFE731-2, Serial No. 7353, Engine Test 9, May 20, 1980 (Cont'd)

Configuration	Condition Number	Total Combustor Airflow, kg/sec	Total Fuel Flow, kg/sec	Primary Fuel Flow, kg/sec	Secondary Fuel Flow, kg/sec	Thrust (Corrected) kN	Combustor Inlet Temperature, K	Combustor Inlet Total Pressure, kPa	Engine Inlet Temperature, K	Fuel-Air Ratio (Metered)	Fuel-Air Ratio (Carbon Bal.)	CO_2 % by Vol. (Dry)	COEI, g/kg Fuel	HCEI, g/kg Fuel	NO_xEI, g/kg Fuel (Corr. for Humidity)	Combustion Efficiency, Gas Sample	Comments
A-11D	7094	9.71	0.1389	0.0440	0.0948	9.07	625.5	949.7	295.9	0.0143	0.0141	2.86	10.46	0.83	9.13	99.68	Sub-Climbout
	8094	10.65	0.1583	0.0442	0.1141	10.42	649.1	1063.3	296.9	0.0149	0.0146	2.98	5.42	0.27	11.13	99.85	Climbout
	9094	11.83	0.1865	0.0446	0.1418	12.22	676.8	1214.2	296.5	0.0158	0.0159	3.14	2.49	0.18	13.70	99.93	Takeoff
	8095	9.97	0.1439	0.0438	0.1000	9.42	633.9	979.7	297.2	0.0144	0.0143	2.91	8.34	0.28	9.86	99.78	Climbout
	9095	11.22	0.1708	0.0443	0.1264	11.24	663.4	1132.2	297.4	0.0152	0.0150	3.05	3.68	0.18	12.33	99.90	Takeoff

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